Modelling the Relative Risk of Large Fires across the Informal Settlements of Cape Town

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Declaration of Own Work

I, Samuel Stevens, declare that the work contained in this thesis has not been submitted for any other degree or professional qualification. It represents my own work, except where stated, and was carried out under the supervision of Dr David Rush and Dr Lesley Gibson between September 2018 and April 2019.

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Abstract

Home to an estimated 1 billion people globally, informal settlements are urban environments that are subject to a high risk of extensive fire spread. Their dense layouts and light, combustible building materials often facilitate the spread of fire through tens or hundreds of homes at once, rendering the inhabitants homeless. Tackling this issue requires a sound understanding of the many spatial factors which can contribute to fire spread. The aim of this study was to quantify the relative risk of large fires across informal settlements in Cape Town, South Africa – a city which has a notable history of devastating informal settlement fires. This was conducted primarily by developing a risk-scoring model based on fundamental fire dynamics and a survey of expert opinion on informal settlements. The study included a review of past disaster risk studies to aid the establishment of solid principles for the risk modelling method.

A 'pairwise weighted' risk model was developed, using GIS software to quantify the spatial environment. It showed a good degree of success in identifying settlements that have a history of severe fires, such as Masiphumelele, Imizamo Yethu and Kosovo, as being of very high fire risk. A particular advantage of the model is its ability to recognise three different categories of fire risk, imposed by infrastructural factors both within and external to a settlement, and environmental factors. However, the fire history data used as a metric to verify the accuracy of the model was unfortunately not of sufficient quality to facilitate a rigorous numerical validation of the model.

Fire risk mapping for informal settlements is a relatively new field of research, therefore many potential developments to the model were also proposed. The relationship between climate and informal settlement fire spread is currently poorly understood so it must be studied and adapted accordingly within the risk model. This could further contribute to modelling of seasonally variable fire risk. Furthermore, future methods for modelling risk directly from estimates of settlement density should be developed, to allow for automatic satellite image processing. This would be of great benefit as it would speed up the GIS-based data collation process which proved time consuming for this study.

Acknowledgements

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Nomenclature

A_{av}	weighted average critical patch size (m^2),
$A_{p,i}$	area of a critical patch within a settlement (m^2),
$\beta_{i,j}$	value of comparison between two spatial factors, i and j,
d_r	average distance to formal road (m),
d_s	average distance to fire station (m),
$\Gamma_{i,j}$	normalised value of comparison between two spatial factors, i and j,
P_f	pathways available for fire spread,
r	distance over which radiant heat is transferred (m),
R	annual rainfall (mm)
ρ_d	edge density (m^{-1}),
Sl	slenderness coefficient (m^{-1}),
Sp	average spacing between any dwelling in a settlement and its nearest neighbouring dwelling (m),
t_f	time available for fire spread,
T_{rel}	relative daily maximum temperature above baseline (°C),
θ	average slope angle in settlement (°),
v_f	fire spread velocity,
v_w	annual average wind speed (m/s),
X_A	scaled relative risk attributable to critical patch area,
X_{dr}	scaled relative risk attributable to distance to formal road,
X_{ds}	scaled relative risk attributable to distance to fire station,
X_R	scaled relative risk attributable to rainfall,
X_ρ	scaled relative risk attributable to edge density,
X_{Sl}	scaled relative risk attributable to settlement slenderness,
X_{Sp}	scaled relative risk attributable to dwelling spacing,
X_T	scaled relative risk attributable to temperature,
X_θ	scaled relative risk attributable to slope angle,
X_w	scaled relative risk attributable to wind speed.

Chapter 1 – Introduction

1.1 Problem Statement

Informal settlements – which may also commonly be known as slums, shanty towns or favelas – are home to an estimated 1 billion people globally (UN-Habitat PSUP, 2016). Estimations also suggest there will be further urban population growth of 2.5 billion people by 2050 (UN DESA, 2015), and it is reasonable to expect that hundreds of millions of these will be in informal settlements. The residents of these settlements are highly vulnerable, and are often subject to poor sanitation, limited or no access to clean water, crowded conditions and poor-quality housing (UN-Habitat, OHCHR and UNOPS, 2015). These infrastructural issues often put residents at a significant health risk, and this combined with a frequent lack of secure employment can leave them stuck in deep cycles of poverty (Huchzermeyer & Karam, 2006).

One issue that is often overlooked in mainstream discourse on informal settlements, yet nevertheless is a significant factor in entrenching poverty cycles, is the occurrence of large-scale fires. These fires can tear through an entire settlement in a matter of hours, leaving hundreds or even thousands homeless. A significant recent example was a fire in a slum in Manila in 2017 which rendered an estimated 15,000 people homeless overnight (Villamor & Goldman, 2017). During fires such as this, families can lose not only their homes but also their livelihoods and many important possessions – money, ID documents, and school books to name a few – which may otherwise be stepping stones out of the poverty they find themselves in. There is also the possibility of life-inhibiting injury or even death. A decade ago, global fire-related burn deaths numbered an estimated 300,000 annually, with over 95% occurring in low- and middle- income countries (Mock, et al., 2008), though the most recent estimates suggest that number is now down to 180,000 deaths each year (WHO, 2018). It is not clear how many of these deaths occur in informal settlements specifically, but it can be reasonably assumed that many do, due to the high proportion of the global population living in such settlements and the vulnerability to which they are subjected.

Statistics are clearer and more specific on a case-by-case basis, better helping to quantify the issue. Taking the nation of South Africa as an example, the most recent available statistics show that there were 5448 informal settlement fires in 2015, resulting in 219 deaths and direct financial losses of nearly R135 billion (approximately £7 million) (FPASA, 2017). Earlier statistics from the MANDISA project suggest that from 1990-2004 there were 8787 fires in the City of Cape Town alone, which burned down a total of 41,301 dwellings (Twigg, et al., 2017). In fact, Cape Town is a city which has exhibited a significant vulnerability to informal settlement fires. As recently as March 2017, a fire in the city's Imizamo Yethu settlement left around 15,000 homeless (Brandt, 2017), and the recovery process is still an estimated two years from completion (Mortlock, 2018).

It is clear that these informal settlement fires are a significant issue, yet the fundamental principles that influence the spread of these fires are still not particularly well understood. At the level of an individual dwelling it has been shown experimentally that a fire can grow to involve the full dwelling in less than 90 seconds (Walls, et al., 2017), with burnout and collapse occurring in as little as 2-5 minutes (Walls & Zweig, 2017). This represents extremely rapid development when compared with a typical compartment fire in the formal built environment and is a significant danger to residents. However, the spread of fire beyond a first dwelling or structure is far more difficult to study, understand and quantify. Evidence so far would suggest that a combination of light building materials, small dwelling spacing, and wind conditions contribute to spread of fire through a settlement in a manner similar to wildfire spread (Walls, et al., 2017). Settlement density (Smith, 2005), access routes and slope (Rosenberg, 2013) have also been mentioned as potential contributory factors, though also with no meaningful quantification of their effects. Examining statistics available for fires in Cape Town over the period 2009-2015, it can be seen that a significant proportion of fires do not actually spread beyond the dwelling of origin (City of Cape Town, 2018). Indeed, from this data it was found the average recorded fire in that period affected less than seven dwellings. Yet, when a fire is able to spread uncontrollably, large scale destruction can occur and hundreds or thousands of people may be left homeless.

1.2 Aim and Objectives

The aim of this work is to understand and quantify the relative risk of fire spread due to spatially varying factors across the informal settlements of Cape Town, South Africa. To meet this aim, the proposed objectives were to:

1. Review previous fire and disaster risk studies to discern effective methods for quantifying risk,
2. Outline the specific context and definition of 'risk' within the scope of this study,
3. Determine the spatial factors of relevance to informal settlement fires and model their relationships with risk in view of current knowledge and literature,
4. Construct a risk-scoring model to determine relative fire risk of Cape Town's informal settlements,
5. Compare the risk-scoring model with City of Cape Town fire history data to determine its applicability, and propose suitable functions of the model.

1.3 Fire Risk Mapping

It is vital to identify which spatial factors play the most significant role in promoting or inhibiting fire spread, so that these factors can be targeted as the basis for future developments designed to limit such spread. The spatial quantification and mapping of fire risk, dependent on these factors, could be a significant visual tool for facilitating this. Mapping of fire risk has already been conducted for several purposes worldwide in the context of both urban fires and wildfires. These studies could help to inform a new method for quantifying and mapping the relative fire risk of informal settlements.

1.3.1 Urban Fire Risk Mapping

Previous studies of urban fire risk have been highly variable. Certainly, the geographic locations and degree of formality of past study areas are diverse. Furthermore, there have been different methods used to conceptualise and score risk. These methods are worth investigating as some may be partly applicable to the mapping of risk in Cape Town's informal settlements.

One apparent method for classifying risk is based on the spatial distribution and severity of past fires. This method was utilised in a recent study of Delhi, with data collected concerning the number of fires, deaths and injuries per administrative district as well as the 'severity' of fires where 'severity' is implied by the number of fire engines dispatched to a fire scene (Tomar, et al., 2018). The overall 'fire risk score' for each district was calculated by the function:

$$Score = (Probability \times Consequence) + Severity$$

'Probability' is an assigned score based on the number of historical fires in a district, 'consequence' is a score based on numbers of fatalities and injuries, and 'severity' is a score based on the number of fire engines dispatched to past fires. This seems a simple and intuitive method for quantifying risk. It represents the definition of risk stated within the study that "fire risk assessment is twofold", relying on both the probability of a fire occurring and the vulnerability of people and the environment exposed to the fire (Tomar, et al., 2018). However, nowhere within this study was it recognised that the spatial and physical environment has any role in influencing fire risk.

Similar to the work of Tomar et al., a study concerning the placement of new fire stations in the city of Sharjah, United Arab Emirates also utilised fire history as a method to quantify fire risk. In this instance, fire risk was not explicitly calculated but was implicit in the GIS-based mapping of areas suitable for locating new fire stations (Yagoub & Jalil, 2014). In addition to fire history, several spatial factors were considered, largely concerning the distribution of social services. This included an imposed condition that a new fire station should be located no closer than 1 km and no further than 9 km from an existing fire station, as recommended by Liu et al. (2006). This implies that all areas of the urban environment should be in sufficient proximity to a fire station to facilitate quick suppressive measures, minimising risk associated directly with the development of a fire. Yagoub and Jalil may only consider this single element of direct fire risk but at least they made some attempt to incorporate features of the spatial environment, which Tomar et al. failed to do. Whilst the city of Sharjah and the informal settlements of Cape Town are completely different urban environments, a functional fire service response is a universally important requirement for reducing fire risk.

As part of a study of the city of Trabzon, Turkey, several spatial factors of potential relevance to informal settlements were considered. Fire engine travel time, fire hydrant locations and the locations of high-risk land use – for example, flammable gas and liquid storage – were all mapped, though only as individual factors and not combined into an overall risk score (Nisanci, et al., 2012). Furthermore, the monthly variation of fire occurrence was examined, showing a dramatic increase in the occurrence of fire in the winter months. This suggests it is pertinent to consider climate and weather variations in the assessment of fire risk. As with the Delhi and Sharjah case studies, fire history was also discussed as contributing to risk.

Comparative to the case studies identified thus far, an older study from the city of Vientiane, Laos incorporates a relatively comprehensive set of physical factors as components of the overall risk score. Several of them could be applicable to informal settlements. Road access, building density, availability of water sources and type of building materials were all included, with all factors simply weighted and added up to produce an overall risk score for each square in a city-wide grid (Lao Urban Research Institute, 2004). Such a method is simple and efficient, though, in this instance, the justification of how the different factors were weighed against each other is not clear. Fire history was again included as a component of the overall risk score.

The only study to be identified as not incorporating fire history within the overall concept of fire risk is one concerning a small area in the Seixal district of Lisbon, which classifies risk on a building-by-building basis. The physical environment appears to have been considered as highly influential in the spread of fire, including several factors that could also be of relevance in informal settlements. Firefighting access, fuel load, building compartmentation and overall condition, and the gap between adjacent openings were all included as components in the calculation of an overall fire risk score (Ferreira, et al., 2016). Whilst a building-by-building analysis would be largely inapplicable to informal settlement fires given the settlement-wide scale of fire, the relevance of the Seixal study is the inclusion of many physical factors and their incorporation into a nuanced weighted calculation to produce an overall fire risk score. A further advantage of the methodology was that it was entirely GIS-based, and the results of the risk assessment were very easily mapped and easy to understand. Indeed, Ferreira et al. (2016) state that GIS is "an effective tool in the support of mitigation strategies and management of fire risk at an urban scale".

One significant issue with most of these studies is that the possibility of fire spread between buildings is nowhere explicitly considered within the framework of risk. This is excusable as it is normally expected that a fire will not spread beyond an individual compartment or building in the formal built environment. However, the entire premise of the problem of informal settlement fires is exactly that they are not constrained to individual dwellings but instead spread quickly and extensively. A single study was identified that, to some extent, deals with the spread of fire due to informality. Fire risk was mapped across the Makola market in Accra, Ghana, where fires were prevalent due to poor quality electrical supplies, reliance on open flame cooking methods and densely packed, flammable market stalls (Oteng-Ababio & Sarpong, 2015). The method of scoring risk was fairly rudimentary and subjective – areas were qualitatively identified as low, medium or high risk based on community observations – but the study does at least provide some insight into features that could be common in informal settlements. Concerning spatial features that influence fire spread specifically (not ignition), the lack of fire hydrants and high density of market stalls were identified as particular problems. It was the only identified study in which some possible fire protection strategies in terms of modifying the physical space were also identified, though discussing them is not necessarily within the scope of this work.

A further issue evident through all of the discussed case studies is a lack of clear distinction between risk of ignition and risk of fire spread. The Seixal study (Ferreira, et al., 2016) is the only one in which it is explicitly stated which physical features of the urban environment are relevant to risk of ignition, and which are relevant to the propagation of fire. Yet even in the Seixal study, all the physical factors were lumped into one single fire risk score. This work is solely concerned with the spread of fires in informal settlements and not their ignition. Therefore, care will be taken throughout the process of identifying and classifying risk to clearly identify how the chosen spatial factors relate specifically to fire spread.

The methodology of this study should also vary from the discussed works in another key way. As noted, ‘fire history’ is incorporated within the calculation of fire risk in several of the case studies, whether that be the number or spatial distribution of past fires, or number of deaths. For this study, this method is deemed to be invalid. Ultimately, fire risk depends on physical and chemical phenomena, and is not temporally constant at a given point in space. For example, fire risk scoring based solely on fire history, as conducted in the Delhi study (Tomar, et al., 2018), does not actually quantify present and future fire risk imposed by the built environment; it simply quantifies the effects of past fires. Incorporating fire history alongside physical factors as a component of risk scoring was the chosen method in many of the other case studies. However, the most appropriate method should be to develop a risk-scoring framework subject to only the spatial environment and independent of fire history. The fire history can then be used to verify the resultant risk distribution across the study area. If the built environment across a given area has not undergone any significant physical changes since the period over which fire data was recorded, the proposed risk classification should reflect fire history data. Yet, no urban fire risk studies have been identified which utilise this method.

1.3.2 Wildfire Risk Mapping

As already noted, the problem of fire spread between buildings is not necessarily of any concern in urban environments, as evidenced by the majority of the urban case studies. However, within the Makola market study (Oteng-Ababio & Sarpong, 2015) and, to some extent, the Vientiane study (Lao Urban Research Institute, 2004) it is recognised that fire risk in informal environments is influenced by the fire's ability to spread from building to building. To understand physical factors relevant to such fire spread, it is pertinent to look beyond the urban environment. The concept of fire spread risk is better acknowledged, and quantified by far more nuanced methods, in the field of wildfire risk mapping. It is expected that some of the spatial factors which contribute to wildfire spread will also influence informal settlement fires. Certainly, informal settlement fires are already observed to behave as some combination of classical compartment fire dynamics and wildfire dynamics (Walls, et al., 2017). Several studies in wildfire or forest fire risk mapping have been identified, again representing a range of different locales and methodologies.

In contrast to the diverse range of works on urban fire risk mapping, wildfire risk mapping studies seem to follow similar processes with the selection of physical and spatial risk factors being fairly consistent across them. It is possible to identify which factors could be influential in the informal settlement environment – those that are common to most wildfire studies but independent of vegetation type. These factors, and the case studies in which they are present, are given in Table 1.1. The physical factors given were quantified in multiple different ways across all the case studies, however, the methods of quantification are of no particular relevance. It is merely the identification of factors which could play a fundamental role in informal settlement fire spread that is of importance.

Table 1.1 - Spatial Factors in Wildfire Studies of Relevance to Informal Settlement Fire Spread

Spatial factor considered	Location and case study					
	Brazil (Eugenio, et al., 2016)	**China** (Gai, et al., 2011)	**Portugal** (Catry, et al., 2009)	**Thailand** (Burapapol & Nagasawa, 2017)	**Turkey** (Akay & Erdogan, 2017)	**Turkey** (Sivrikaya, et al., 2014)
Slope	✓*	✓	-	✓	✓	-
Aspect	✓	✓	-	✓	✓	✓
Temperature	✓	✓	-	-	-	-
Altitude	✓	✓	✓	-	-	-
Access by road	✓	-	✓	✓	-	✓
Moisture**	✓	✓	-	✓	-	-
Wind	-	✓	-	-	-	-
Fire suppression measures	-	✓	-	-	-	-

*A tick (✓) indicates the inclusion of the relevant physical factor in the given study.
**Studies were considered to have taken moisture into account if they included any one of soil moisture, humidity or precipitation.

Whilst the variation in selected factors between wildfire studies is not as diverse as between urban studies, it can be seen there are still some significant differences between them. These differences are worth some discussion. Firstly, it is worth re-emphasising that the factors given are only those that are of potential relevance to informal settlements. Within each of the case studies, consideration was made for a further array of factors that depend on the type, condition and density of vegetation, and the land use. Vegetation-related factors essentially define the contribution of the fuel load to fire risk, and so for informal settlements these should be replaced by factors concerning the nature and density of the fuel load, which is the settlement itself and the contents of dwellings. In addition, factors concerning land use can be reasonably neglected for informal settlements as the land use is essentially a constant state – informal dwellings.

Furthermore, some studies lack any explicit consideration of temperature or moisture, yet these factors may be dealt with implicitly by aspect. The aspect of a slope – its orientation relative to the primary direction of sunlight – will influence both the temperature and moisture associated with that location. As such, only the work of Catry et al. (2009) did not incorporate temperature and moisture, and this omission may simply be due to the fact that the study was conducted to quantify only ignition risk.

In all but one of the case studies – the work of Gai et al. (2011) – there was a surprising lack of consideration of the effects of wind, especially given longstanding knowledge of the high influence of wind on wildfires (Beer, 1991). It is noteworthy that high altitudes may imply stronger winds, thus greater fire risk. Yet, in both studies in which altitude, but not wind, was considered, wind conditions were not even mentioned in the context of altitude (Catry, et al., 2009; Eugenio, et al., 2016). Furthermore, in both studies, increasing altitude was in fact taken to indicate decreased fire risk. This suggests that, whilst physical factors present in wildfire risk mapping can be of relevance to informal settlements, the quantitative methods applied to calculate risk should not necessarily be the same for both environments. Another notable example of this is evident in the work of Burapapol and Nagasawa (2017), in which greater steepness of slope correlates to a lower probability that the land is occupied by people or vegetation. Thus, there is a reduced likelihood of *ignition* so a lower overall wildfire risk score. This correlation would be fundamentally incorrect to apply to fire *spread* in informal settlements, given that fire spread velocity is known to increase with slope steepness (Butler, et al., 2007), thereby increasing fire risk.

One wildfire case study that is particularly significant is the work of Catry et al. (2009), in which the probability of wildfire ignition was mapped spatially across the whole of Portugal. The premise of the work differs from this study of informal settlements given it concerns only ignition and not fire spread. However, it is highly significant because of the use of regression techniques to build a mathematical scoring model that incorporated datasets directly. That is to say, the data values are not lumped into cruder scored categories before being used to quantify risk. In every other case study discussed so far (including the urban case studies), where an overall risk score was calculated, some variation of categorised scoring was applied. It may be possible to use similar regression techniques to build a direct, rather than categorised, risk scoring method for application to

Cape Town's informal settlements. Furthermore, Catry et al. proceed to compare their spatial risk map with recorded data of wildfire ignitions in Portugal over a five year period, finding a good level of fit. Whilst the specifics of the comparison are not relevant, it otherwise represents an important step for verifying the accuracy of the fire risk mapping method. However this is a step that is apparently lacking from most previous attempts at both urban fire and wildfire risk mapping. Indeed, the only other identified case study which includes some attempt at comparison of fire history to the proposed risk model is Burapapol and Nagasawa's mapping of wildfire risk in Thailand (2017).

1.3.3 Large Disaster Risk Mapping

GIS-based mapping has also been used as a means of visualising the spatially-varying risk presented by other large-scale disaster types, namely earthquakes, tsunamis, flooding and landslides. Analogous to past fire risk studies, natural disaster risk studies are also diverse in both function and geographical location. Across previous studies, there are many identifiable elements of the risk-mapping process which may also be applicable to a method for fire risk mapping. However, it is also important to note the features that are prominent in wider disaster risk studies but should not be of relevance to fire risk mapping in informal settlements specifically.

The primary difference is the increment in scale over which these natural disasters can occur. Where an informal settlement fire will generally not extend past the settlement in which it begins, these larger disasters can cause destruction at the scale of whole cities, states or even nations. It was previously mentioned that, within informal settlements, variability of land use can be reasonably neglected within the scope of a risk study. This is not the case for disasters on these larger scales, as they would be expected to impact a vast array of land uses and socioeconomic demographics. Inevitably, previous studies which have attempted to quantify risk have therefore done so in a manner that does not explicitly visualise risk presented by the physical environment, instead favouring the presentation of socioeconomic vulnerability. A particularly favoured method is the estimation of cost of damage for given exceedance probabilities as has been conducted for seismic activity in Germany (Tyagunov, et al., 2006) and for seismic activity and flooding in Costa Rica (Van Westen, et al., 2002). There is even evidence that the physical environment is sometimes completely neglected as a feature of vulnerability to disasters, as was the case with a study comprising the scoring and mapping of socioeconomic vulnerability in Mumbai, India (Sherly, et al., 2015). It is useful to understand how varying land use, economic and social factors contribute to the outcome and cost of disasters, yet these studies are not particularly useful for informing the development of physical mitigation strategies. For example, it may indeed be the case that a particular community is socioeconomically deprived, but, by virtue of beneficial location, may not actually be 'vulnerable' in the context of a disaster.

Nevertheless, wider disaster risk studies are generally more nuanced than current urban fire risk studies. An earlier identified problem of the fire studies was the tendency for fire history to be used as a factor in risk scoring, rather than as a means of method verification. In contrast, other disaster studies have utilised historical data of injuries, fatalities and damage distribution as a tool to identify features of the physical environment that could contribute to a risk-scoring method. Examples include attempts to establish relationships between flow depth and rate of destruction from the damage patterns observed after the Indonesian Boxing Day tsunami of 2004 (Leone, et al., 2011), and the spatial mapping of damage and injuries as a result of the 1994 Northridge, California earthquake to examine how the physical environment contributed to injury risk (Peek-Asa, et al., 2000).

A further success of many wider disaster risk mapping studies is the clarity with which the applied weighted scoring method is presented and the resultant spatial risk distribution is mapped. The most robust scoring methods clearly identify the physical factors being considered, the production of their relative weights of influence, and their mapping both individually and as an overall risk score. The most prevalent risk-scoring method identified across multiple studies to meet these ends is a method known as a 'pairwise comparison', in which all physical factors are weighted against each other to evaluate their overall weighted contribution to risk. Whilst the specifics are not necessarily relevant at this point, it is noteworthy that this method provides a clear, concise and logical method for combining many physical factors into a risk-scoring model. Indeed, it has been utilised for scoring and mapping risk pertaining to disasters as diverse as flooding in Kenya (Ouma & Tateishi, 2014), landslides in Pakistani Kashmir (Kamp, et al., 2008), and tsunamis in Bali, Indonesia (Sinaga, et al., 2011). In all of these studies the produced risk maps were clear, lending themselves to immediate identification of 'at risk' areas, to potentially be targeted for development.

As with wildfire risk mapping studies, wider disaster risk studies contain principles that are applicable to informal settlement fire risk mapping. In particular, some exhibit clear methods for building a risk-scoring model that have been applicable across several disaster types in diverse locations, so should therefore be equally applicable to the informal settlement context. In some past studies, the importance of the physical environment is slightly obscured by consideration of spatially varying socioeconomic conditions, to the detriment of understanding physical risk, so it is important to consider if and how socioeconomic factors may contribute to informal settlement fire risk.

1.3.4 Summary

The quantification and mapping of fire risk can be a powerful tool for visualising the spatial variation of risk and informing potential development projects. Much can be understood from past studies concerning the mapping of urban fire and wildfire risk that may be applicable to the mapping of risk across Cape Town's informal settlements. Primarily, several physical and spatial factors have been identified from previous studies that should also be of importance to consider in the context of informal settlements. It has also been found that risk scoring models usually rely on collected data being allocated into scored categories, though it is possible to formulate models that incorporate data directly. In addition, the comparison of a risk-scoring model against corresponding fire history is often neglected but should be viewed as an important step in the verification and further development of such a model. In general, the overall quality of each study was partly influenced by how risk was defined within the study and whether there was any distinction between risk of ignition and risk of fire spread. Quantification methods applied in these studies, and others concerning larger disasters, may provide insight into how fire risk could be quantified in informal settlements. However, it is clearly important to understand the balance of physical and socioeconomic factors within the wider scope of risk – it is not ubiquitous across different scenarios. All of these concepts should be considered when trying to understand and quantify the risk of fire spread across the informal settlements of Cape Town.

Chapter 2 – Establishing the Foundations of a Risk Model

2.1 Defining 'Risk'

The concept and definition of 'risk' is not constant across past studies. Therefore, it is vital to begin by clearly and concisely defining how the term is applied specific to this study.

Previous studies do not always distinguish well between features of the environment which contribute to ignition risk and features that contribute to fire spread risk. However, the scope of this work only concerns fire spread through informal settlements, and not ignition. As an illustration, consider a single informal dwelling in which ignition has already occurred and the fire has fully involved the structure. The intention of this study is to quantify the posed risk to the wider settlement as a result of potential fire spread from this initial dwelling. As a result, every physical and spatial factor that will be included in this study will be considered only in the context of its contribution to fire spread.

The general definition of risk is a scenario which involves *exposure or vulnerability to a threat*. In the case of any fire risk mapping study, the obvious threat is the fire itself. However, it remains necessary to also quantify the exposure or vulnerability to the fire, normally a function of population density and economic value (land use and property value). This poses a problem to the case of informal settlements for two primary reasons. Firstly, it would take the lengthy extraction of population data from past census results to build an understanding of variance in population density and demographic across such settlements. This is particularly difficult given that Cape Town's administrative wards tend to include areas of both formality and informality. Secondly, residents may rely on income from informal employment which, though it may be recorded in census data, is not necessarily stable or well quantified at the settlement level. This makes it incredibly challenging to assess the relative economic value of each individual settlement. In South Africa, informal enterprise may include childcare, shops, hairdressers and construction work (Sustainable Livelihoods Foundation, 2011), and is estimated to constitute 33% of all non-agricultural employment (Vanek, et al., 2014). In general, this is an area of understanding that requires future work but is not within scope of this study.

It is clear that quantifying the relative vulnerability of each informal settlement would be a difficult process, so for the purposes of this study it is simply assumed that the vulnerability of all settlements is the same. In simple terms, if an equal spatial area in two separate settlements was destroyed by fire, the losses sustained by each settlement – whether that be material or economic losses – are taken to be equal. Whilst this may not be true in reality, it is an assumption that allows variance of settlement vulnerability to be negligible within the overall definition of risk. Risk can be conceptualised as a function of the threat alone. Thus, for this study, 'risk' is simply defined as *the likelihood that a fire will spread extensively across an informal settlement, as a result of the physical and spatial characteristics of the settlement*.

2.2 Quantifying Fire History

The produced risk-scoring model was refined with respect to externally existing opinion, literature and data. One significant focus was to compare such a model with data of informal dwelling fire history in Cape Town. Doing so, established if the weighting of spatial factors within the model correlates to the severity of past fires.

Fire data was recorded in Cape Town over the period 2009-2015, and identifies the occurrence and size of informal dwelling and settlement fires (City of Cape Town, 2018). The data was mapped showing areas where high numbers of fires have occurred (Figure 2.1) and where there have been high total losses due to fire (Figure 2.2). When considering the risk of fire spread, the primary concern is the average fire size – a dataset that was produced by simply dividing the number of dwellings destroyed by the number of fire incidents. This 'average fire size' dataset (Figure 2.3) provided data against which the eventual risk model was compared.

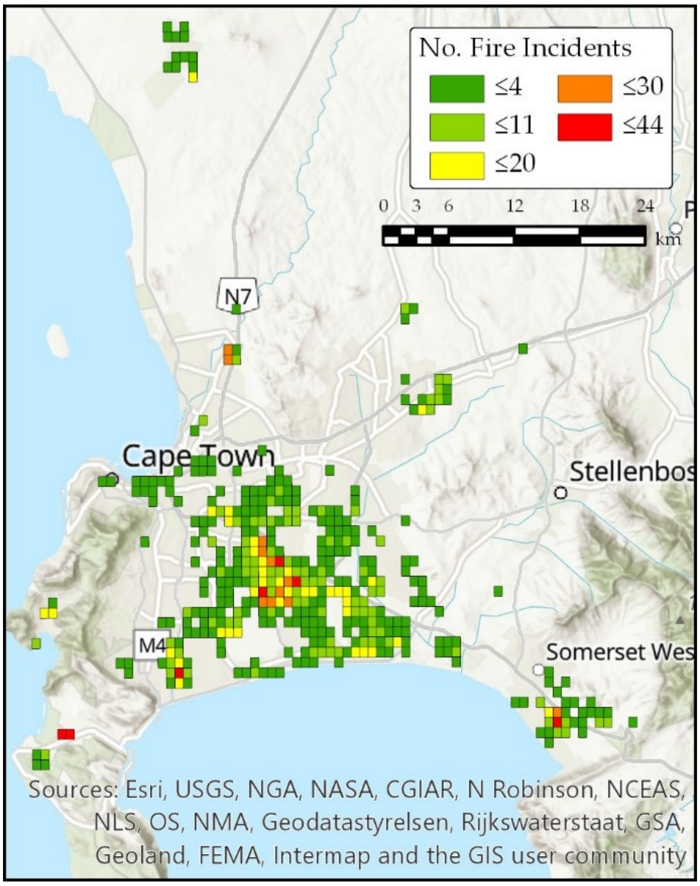


Figure 2.1 - Number of Fire Incidents, 2009-2015 (City of Cape Town, 2018)

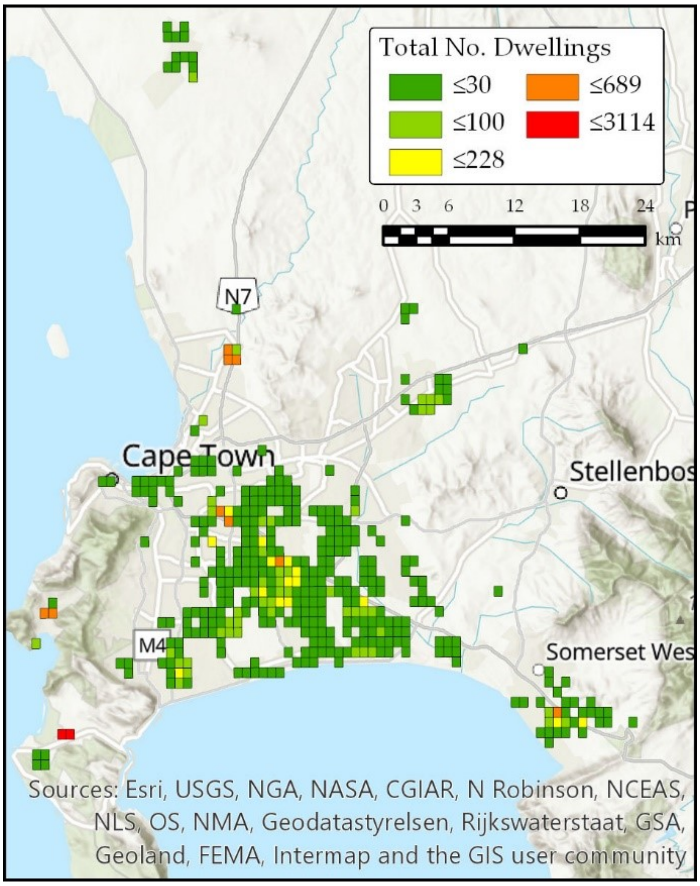


Figure 2.2 - Total Number of Dwellings Destroyed, 2009-2015 (City of Cape Town, 2018)

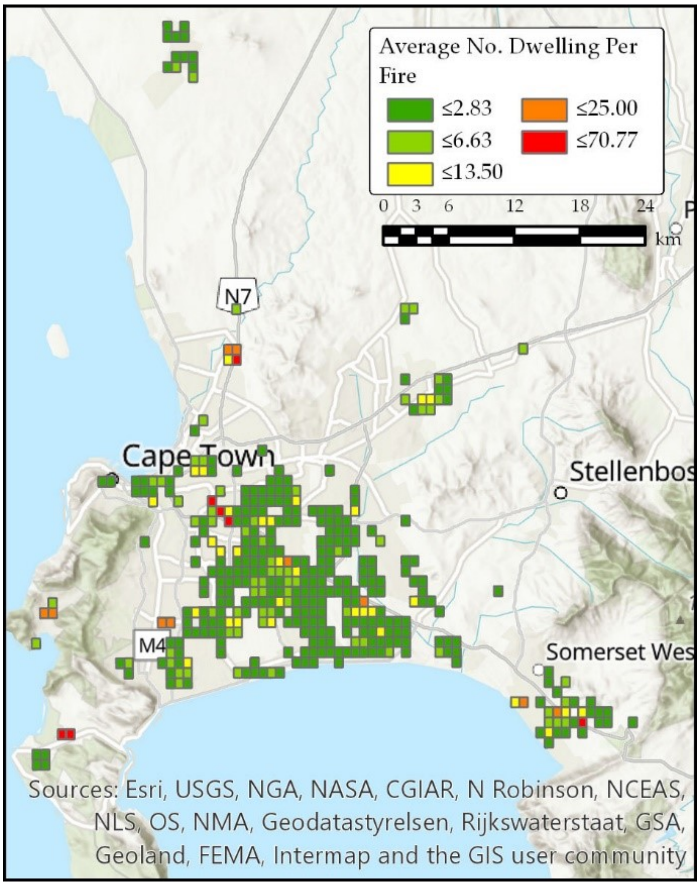


Figure 2.3 - Average Number of Dwellings Per Fire, 2009-2015 (City of Cape Town, 2018)

2.3 Data Collection

In the most general terms, the fundamental mechanisms of flame spread are controlled partly by the orientation of fuel and environmental factors (Drysdale, 2011). At a settlement level these concepts can be related to specific physical and spatial factors. 'Fuel orientation' encompasses the layout of a settlement (density, dwelling-to-dwelling spacing) and topography whilst 'environmental factors' include air flow (wind), ambient temperature and presence of moisture (rainfall). Suppression is also relevant to how a fire may spread, and in the context of an informal settlement specifically relates to fire-fighting access and infrastructure.

To build a picture of the scope of fire risk in Cape Town, several datasets were obtained to be processed in ArcGIS Pro software (hereafter named 'ArcPro'), with the aim that the data could contribute to the risk scoring model. The datasets and the spatial factors for which they were required to calculate are given in Table 2.1.

Table 2.1 - Collected Datasets

Dataset	Spatial factors developed from dataset	Source
Average wind speed at 50m above ground	• Wind speed	Wind Atlas for South Africa (Riso DTU, 2019)
Digital Elevation Model (DEM)	• Slope	City of Cape Town Open Data Portal (City of Cape Town, 2015)
Monthly average of daily maximum temperature (x12)	• Temperature	South African Atlas of Agrohydrology and Climatology (Schulze, 1997)
Road centrelines	• Proximity to roads	City of Cape Town Open Data Portal (City of Cape Town, 2015)
Fire stations	• Proximity to fire station	City of Cape Town Open Data Portal (City of Cape Town, 2016)
Dwelling rooftops	• Average dwelling spacing • Critical patch size • Edge density	Privately commissioned by IRIS-Fire, to be published in due course
Informal settlement boundaries	• Settlement slenderness • Edge density • Proximity to roads and fire station	Manually developed in collaboration with Dr Lesley Gibson from the dwelling rooftop layer
Annual rainfall	• Rainfall	South African Atlas of Agrohydrology and Climatology (Schulze, 1997)

The many functions of ArcPro allowed for relevant data to be calculated for each of the spatial factors and then attributed to areas outlined by the informal settlement boundaries. There are some uncertainties introduced by this informal settlement layer. Given it was developed remotely, it was not always possible to define where one 'settlement' ends and another begins. As such, the term 'settlement area' will be used to describe an element of this dataset, as multiple 'areas' may make up what is recognised as a single settlement in reality. Effectively, in some cases, the eventual risk scores are calculated to a higher resolution than the whole settlements. This is particularly beneficial for settlements that are large enough that the scope of risk may vary drastically cross them.

It is noteworthy that many of the settlement areas are simply named as '*Unknown##*' due to their remote identification and lack of nomenclature on open source web mapping software. It may be the case that the names of smaller informal settlements are only known locally, however, they can still be identified by their locations in the GIS dataset.

The focus of subsequent discussions will be on the relation of spatial factors to fire risk, but the basic datasets which were used or developed are mapped in Appendix A. The locations of all informal settlements processed in this study are given in Figure 2.4, highlighting settlements and regions that are of importance to the later analysis. At the scale of the whole dataset, it is not possible to visually identify individual settlements areas, but these will be identified more clearly where analysed in detail.

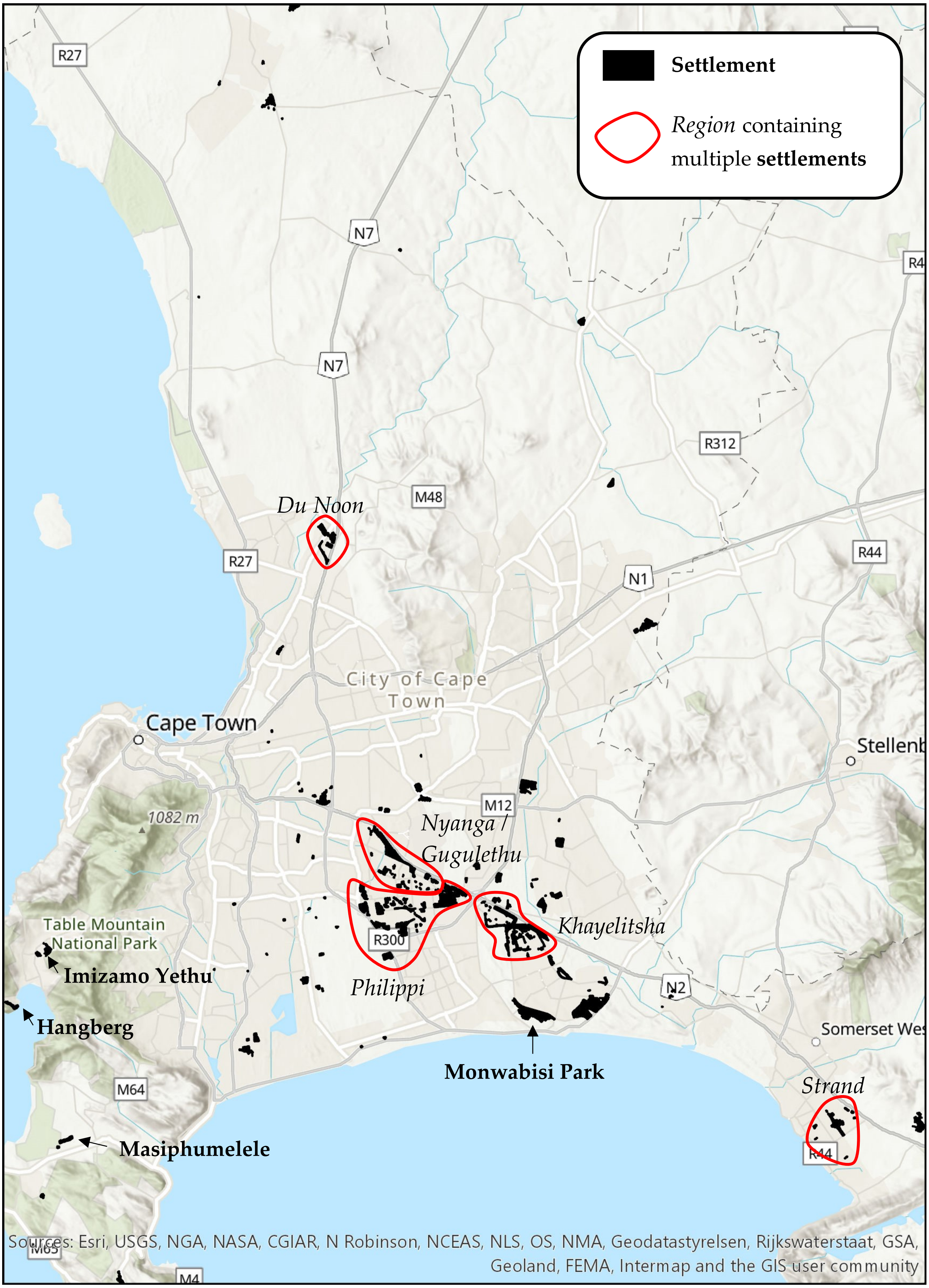


Figure 2.4 - Informal Settlement Locations, Identifying Some Key Settlements and Regions

2.4 The Paradigm of Fire Spread

The complexity in developing a robust risk-scoring model lies with the need to logically relate risk to the physical principles underlying each spatial factor, whilst maintaining a clear and concise methodology. The majority of past risk mapping studies utilised a lumped risk-scoring method, which sorts data into discrete categories, prior to weighting the different factors by relative influence. Whilst lumped scoring is quick and efficient, it is not always clear how the scoring method relates to the fundamental dynamics of fire spread.

The following method was developed for logically relating risk to fundamental components of fire spread. There are three components of fire spread influenced by the spatial environment:

- **Rate** of spread,
- **Pathways** available for spread,
- **Time** until effective suppression.

Rate of spread means the rate with which a fire moves from one dwelling to the next, neglecting the wider settlement environment. It is generally a function of environmental factors and the layout of dwellings relative to one another due to slope and dwelling spacing.

Factors concerning pathways for spread influence the spatial extent over which a fire can spread through the wider settlement *at any given rate.* This is where the size, layout and shape of the wider settlement play a significant role, with settlement slenderness, edge density and critical patch size being the relevant factors. Given a constant rate of spread, it should be only these factors that define the area of a settlement destroyed by a fire in a certain time.

The time during which a fire can spread unhindered is limited by when firefighting activities begin. This depends on the distance of a settlement from the nearest fire station and the ability of the fire service to then access the fire.

The complex interactions between all spatial factors can be simplified by identifying the single component of fire spread which that factor predominantly affects (Table 2.2). This concept provided a basis for relating each spatial factor to risk independentlyChapter 3), resulting in a clear and logical risk-scoring model that does not rely on crude lumped scoring.

Table 2.2 - Spatial Factors Listed by Component of Fire Spread they Predominantly Affect

Rate	Pathways	Time
• Wind • Rainfall • Topography • Temperature • Dwelling spacing	• Settlement slenderness • Edge density • Critical patch size	• Proximity to roads • Proximity to fire stations

Establishing clear, logical risk distributions as a function of each individual spatial factor relied on an understanding of how each of the rate of spread, pathway availability and time relate directly to fire spread risk. However, the dynamics of fire spread through informal settlements make these relationships complex, so some simplifications were required.

It has already been established that the definition of risk within this study neglects vulnerability, so it was reasonably concluded that risk varies linearly with area burned:

$$Risk \propto Area$$

In the case of available pathways, a linear relationship with risk can be assumed – after all, the more physical points in the settlement through which a fire travels, the greater the area burned.

Therefore,

$$Risk \propto P_f$$

With,

P_f pathways available for fire spread.

However, area-dependent risk becomes more complicated when studying the development of burnt area in time and at different spread velocities. Consider two scenarios, one in which a planar fire front spreads in one direction, the second in which a circular fire front spreads radially, at equal velocities (Figure 2.5). It is clear that the area burned will vary with both speed (v_f) and time (t) linearly in the former scenario, and as a square function in the latter.

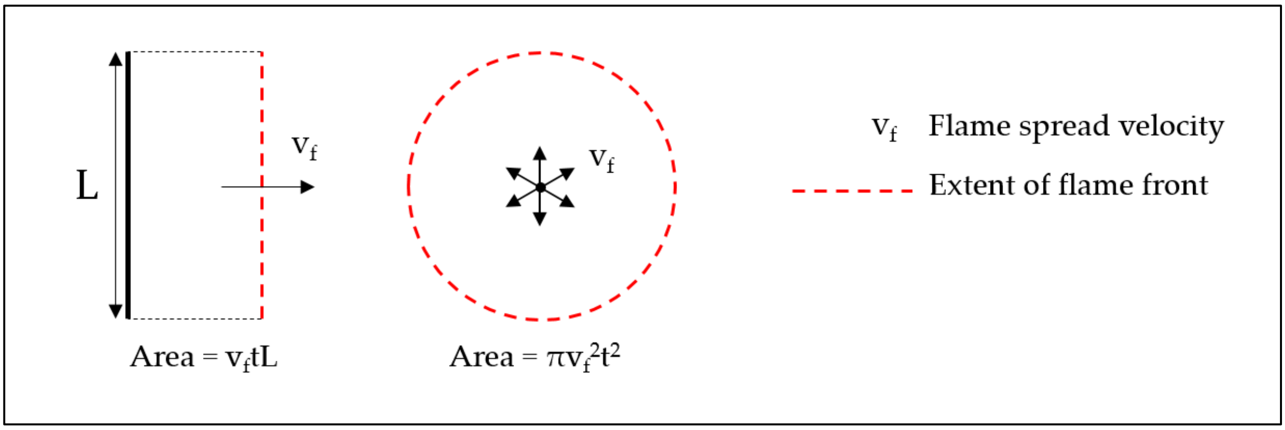


Figure 2.5 - Planar vs Linear Flame Spread

In reality, informal settlement fire spread is rarely perfectly planar or radial due to the influence of wind. Even if a planar fire front develops, it still must have originated at a single point, necessitating some initial lateral spread. Generally, fire spread is expected to be approximately elliptical. Indeed, many post-earthquake fire modelling methods, up to and including the relatively recent work of Lee and Davidson (2010), are verified against an elliptical model of fire spread developed by Hamada (1951). The only identified model to deal specifically with informal settlements also includes an explicit comparison to Hamada's model (Moradi, 2016).

For elliptical fire spread, the rate of fire spread is clearly not constant in all directions, and it is here where the complexity lies. The area burned should vary somewhere between linearly and a square function of time such that,

$$Risk \propto t_f^n$$

$$n \in \{1.0, 2.0\}$$

With,

t_f time available for fire spread.

It is not unreasonable to think that radial fire spread presents the greatest risk as it provides the greatest increase in area relative to time. However, radial spread can only occur in no-wind conditions, which means the fire spread velocity will be slower. To greatly simplify Hamada's numerical model, it can be generally stated that higher wind speeds promote spread in the downwind direction but inhibit the propagation of fire perpendicular to the wind and in the upwind direction. Simply, higher wind speeds encourage the development of a single, steady-state flame front. As already stated, the area burned by such a flame front should vary in an approximately linear manner with both velocity and time. Thus, for simplification, it was assumed that burnt area varies linearly with both time and velocity. So,

$$Risk \propto t_f$$

$$Risk \propto v_f$$

With,

v_f fire spread velocity.

Reducing all of the rate, time and pathway relationships with risk to linear variations greatly simplified the task of quantifying the real physical and temporal role of each individual spatial factor in terms of 'risk'. Note that none of these variables require units – they are simply theoretical variables conceptualised to make logical connections between spatial factors and risk.

2.5 Summary

Within the scope of this study, risk is defined as the likelihood that a fire will spread across an extensive area of a settlement as a result of its spatial characteristics. Economic vulnerability was reasonably neglected from this definition due to the narrow scope of land use and value relative to larger-scale disasters. The foundation of a risk model was established by relating each of three fire spread components – time, rate and pathways – directly to risk. Datasets for processing in ArcPro software were obtained, allowing for the inclusion of ten spatial factors in the risk model. These factors were each related directly to one of three fire spread components to later establish relationships of each with risk.

Chapter 3 – Spatial Factor Relative Scoring

To encapsulate the relative risk contributed by each spatial factor of the settlement, the data pertaining to each factor was converted into a 'normalised' risk score on a scale from 0 to 1. The numerical function of each scale was developed with respect to relevant literature. Each spatial factor was simplified to apply to only one of rate, pathways or time, to develop clear logical relationships between the factor and risk. These relationships were developed with respect to analyses of the ArcPro datasets, and the precise methods are clearly stated where relevant.

3.1 Wind

The role of wind on fire spread is a multi-faceted one. Not only does it fundamentally affect the airflow conditions around the fire, driving the direction in which it spreads; in larger urban and wild fires it also influences the production, size and transportation of firebrands (Zhou, et al., 2015; Suzuki & Manzello, 2019). These brands can travel ahead of a fire, igniting spot fires well beyond the fire front. Due to these diverse roles, conceptualising a precise model of the relationship between wind speed and fire spread was extremely difficult.

The only identified study to model fire spread in informal settlements predicted an increase of wind speed from 0 to 10 m/s would result in a 204% increase in total burned area in the specific case of Cape Town's Imizamo Yethu settlement (Moradi, 2016). However, it was not comprehensive enough to conceptualise a fire spread rate model as a function of wind speed.

Whilst wildfires are different from informal settlement fires in some respects, they do have similar macro-scale dynamics. Sullivan (2009) summarises an array of studies concerned with empirical modelling of wildfire spread, showing a huge degree of variability in past interpretations of the influence of wind speed. Across all the studies, the fire spread rate was modelled as a variety of different linear, exponential and power functions of wind speed. However, few of these models were developed from tests at wind speeds of a similar range to those exhibited in Cape Town. The annual average wind speed within each settlement area boundary was calculated in ArcPro, ranging between approximately 5-10 m/s across all settlements. Of the many studies Sullivan collated, only eight had test results for wind speeds above 5 m/s, with seven of the eight resultant models incorporating a power function of the form:

$$Fire\ spread\ velocity \propto (Wind\ speed)^n$$

$$n \in \{0.844: 3.0\}$$

However, for the only two studies to have data for wind speeds up to 10 m/s (Marsden-Smedley & Catchpole, 1995; Catchpole, et al., 1998), the range of powers was considerably reduced to:

$$n \in \{1.21: 1.312\}$$

Given the lack of other field studies that test wind speeds of the same range as those observed in Cape Town, it is plausible that fire spread will vary with respect to wind speed in a similar manner, as a power function of power $n \approx 1.3$. Therefore, this is taken to apply to informal settlement fire spread (including the possible effects of through draft on radiative heat transfer). The scaled risk score is taken relative to the maximum annual average wind speed experienced by a single informal settlement which is 9.46 m/s.

Therefore,

$$Risk \propto v_f$$

$$v_f \propto v_w^{1.3}$$

$$X_w = \frac{v_w^{1.3}}{v_{w,max}^{1.3}}$$

$$X_w = \frac{v_w^{1.3}}{18.56}$$

With,

v_w annual average wind speed (m/s), $v_{w,max} = 9.46$,

X_w scaled relative risk attributable to wind speed.

3.2 Topography

The angle of slope on which a settlement is situated essentially defines the orientation of the fuel load relative to any potential fire. At the simplest level, a sloped topography results in areas uphill from the flames being subject to a greater radiative heat flux than if it was a horizontal plane. However, unbalanced forces due to the discrepancy between air entrainment at the upslope and downslope edges of the fire can also cause the fire to lean over in the uphill direction, increasing the heat transfer upslope, as is a feature of wildfire burning on slopes (Grumstrup, et al., 2017). This increases the velocity of fire spread up the slope, though Grumstrup et al. note that turbulence conditions differ drastically between small lab experiment and field-scale fires. It may, therefore, be hard to justify applying any relationships that have been derived experimentally directly to the informal settlement context.

Early tests on plain thin fuels such as filter paper and "computer card" generally establish that spread rate upslope increases exponentially with slope angle (Drysdale & Macmillan, 1992). However, on these simple fuels, the rate of increase can be negligible over small changes in slope angle, with one test of PMMA samples exhibiting almost no increase in rate of spread between 0-15°. Flame spread was observed to increase rapidly when a more defined flame front formed at angles above 15°.

More recently, tests have been conducted on fuel beds rather than thin individual fuels, to better understand how wildfires may spread on slopes. Tests by Weise and Biging (1994) established that spread rate certainly increases with slope angle, but no clear relationship was identified as the work focused predominantly on the effects of wind. However, Nelson (2002) later reworked the data to focus particularly on the effects of the slope angle, establishing an approximately linear variation – though data was only available for slopes of 0°, 8.5° and 16.7°. Butler et al. (2007) tested another fuel bed over a more extensive set of slope angles, establishing an approximately exponential relationship. However, similar to Drysdale and Macmillan, they observed that the change in slope eventually induced a change in burning regime. At slopes exceeding a 45% gradient (~25°), the flame spread rate increased rapidly due to the formation of a more defined flame front. At slopes up to a 30% gradient (16.7°), the rate of spread increased in an approximate linear manner (similar to Nelson's work). This is important, given that Cape Town's informal settlements are rarely located on steep slopes. The average slope within each settlement area in ArcPro was calculated, showing none of the informal settlements have an average slope exceeding 19°. Indeed, the vast majority (92%) have average slopes of less than 5°. Butler et al. also note that spread rate can increase downslope with increased angle due to fuel falling or slipping down the slope, though the effects of this are negligible compared to upslope spread.

Given that the range of slope angles exhibited in Cape Town's informal settlements is over relatively low slope angles – 0-18.45° – not exceeding the 25° linear flame front lower limit observed by Butler et al., it is reasonable to approximate the relationship between slope and fire spread velocity as linear.

Therefore,

$$Risk \propto v_f$$

$$v_f \propto \theta$$

$$X_\theta = \frac{\theta}{\theta_{max}}$$

$$X_\theta = \frac{\theta}{18.45}$$

With,

θ average slope angle in settlement (°), $\theta_{max} = 18.45$,

X_{θ} scaled relative risk attributable to slope angle.

3.3 Dwelling Spacing

Fire is enabled to spread if dwellings are in very close proximity, predominantly due to radiative heat transfer. Generally, the closer a dwelling is to an adjacent fire, the quicker it will ignite, though in reality the time to ignition is also governed by the incident heat flux and the orientation or angling of the dwelling towards the fire. The overall model for radiative heat transfer given by Drysdale (2011) implies the relationship between incident radiative heat flux ($\dot{q}''$) and distance from emitting source (r) is of the following form:

$$\dot{q}'' \propto \frac{1}{r^2}$$

Drysdale also gives a model for the time to ignition (t_{ig}) of thermally thin materials[1] which implies:

$$\dot{q}'' \propto \frac{1}{t_{ig}}$$

Therefore,

$$t_{ig} \propto r^2$$

Under specific experimental conditions a material can be found to have a critical heat flux for ignition. If a design fire is known or estimated, this critical heat flux can contribute to the conceptualisation of a critical distance for ignition – in simple terms, the maximum distance the material can be from a fire at which it will ignite. Wang et al. (2018) investigated this theory in relation to informal dwellings in Cape Town and proposed that

[1] Building materials in informal settlements are commonly sheet materials so are likely to act as thermally thin.

they can have a critical distance for ignition of as much as 3.3m if there are polyurethane-type materials present.

It is important to note that, for informal settlement fires, the distance between dwellings and the distance of radiative heat transfer are not equal. This is due to the fact that there will be a plume of combustion gases projected from the dwelling that will be the predominant source of radiant heat. If dwellings are close enough together, this plume may directly engulf an edge of an adjacent dwelling. The extent to which this plume protrudes from the burning dwelling varies with the size and shape of the opening from which it flows, as well as if there is any wind-assisted through draft. The effects of these on risk are complex but Wang et al. model simplified relationships for scenarios with no through draft. These suggest the incident heat flux experienced by an adjacent dwelling is at a constant maximum up to 0.6-1.3m from the burning dwelling depending on opening characteristics, dropping to effectively 0 kW/m^2 at the critical distance of 3.3m. The relationship between dwelling spacing and fire spread risk was therefore conceptualised as an inverse squared relationship with a forced plateau at smaller distances (Figure 3.1).

Since time to ignition is the inverse of rate of spread,

$$Risk \propto v_f$$

$$Risk \propto \frac{1}{t_{ig}}$$

$$Risk \propto \frac{1}{r^2}$$

$$v_f \propto \frac{1}{r^2}$$

$$r = f(Sp)$$

$$X_{Sp} = \begin{cases} 1, & Sp < 0.6 \\ 0.6^2 \times \left(\frac{1}{Sp^2} - \frac{1}{3.3^2}\right), & 0.6 \leq Sp \leq 3.3 \\ 0, & 3.3 < Sp \end{cases}$$

With,

r distance over which radiant heat is transferred (m),

Sp average spacing between any dwelling in a settlement and its nearest neighbouring dwelling (m),

X_{Sp} scaled relative risk attributable to dwelling spacing.

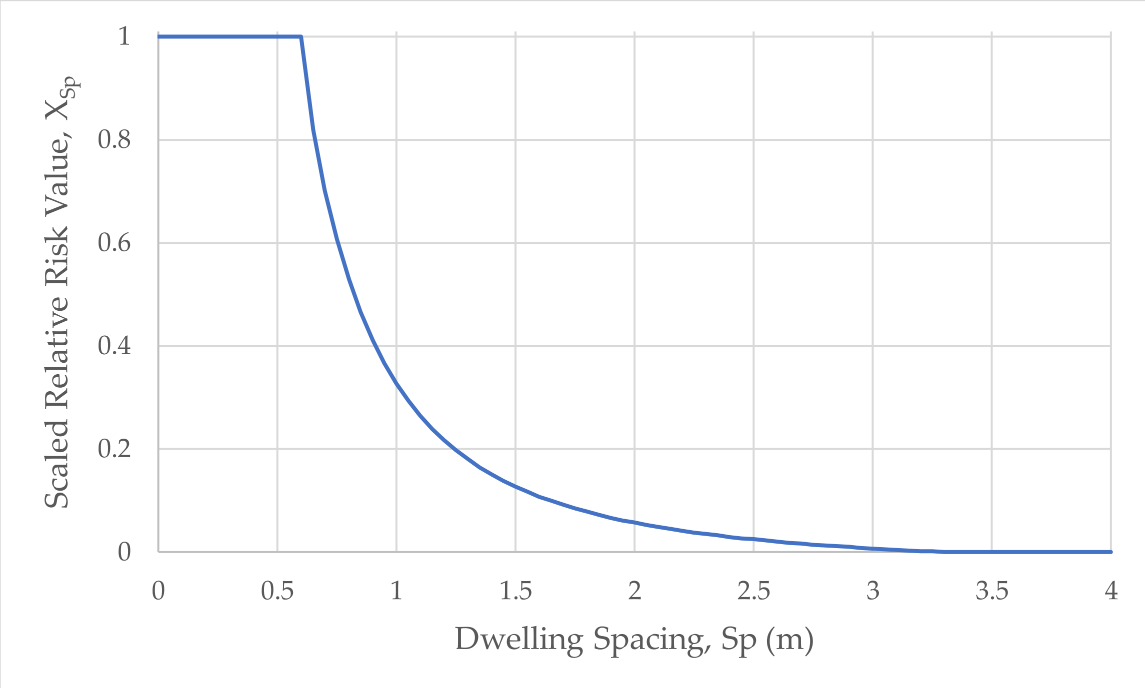


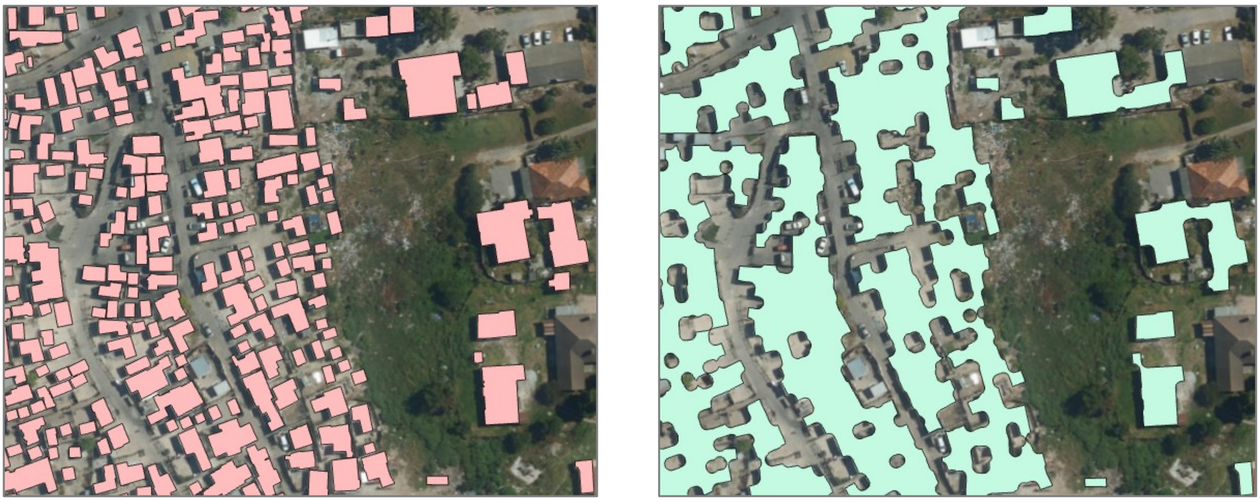
Figure 3.1 - Scaled Relative Risk Variation with Dwelling Spacing

This relationship implies that there is no risk attributable if, across all the dwellings in a settlement, the average spacing from a dwelling to its nearest neighbour is further than the critical distance of 3.3m. However, if the average minimum spacing is less than 0.6m, it is likely flames from a fire in one dwelling will directly impinge upon an adjacent dwelling, thus is the maximum level of risk achievable. The value of 0.6m was preferred over 1.3m as it provides a higher degree of variability and thus a wider scope for understanding the relative influence of dwelling spacing on risk.

Wang's wind-assisted through draft model exhibits both a higher radiative heat flux and an increase in the distance over which the fire can spread. For simplicity this is neglected in the modelling of risk with respect to dwelling spacing, and is assumed to be implicit within the risk-wind relationship (3.1).

3.4 Critical Patch Size

Whilst the average distance of a dwelling to its nearest neighbour indicates the rate at which fire will be able to spread between those two dwellings, it does not provide any indication of how far a fire may be able to spread through the whole settlement. To account for this, the idea of critical distance within informal settlements can be developed further by buffering settlements to a critical distance to form larger 'critical patches'. Returning to the model of Wang et al. (2018), where the space between two dwellings is 3.3m or less, this can be considered to be a continuous path for fire spread, in the absence of firefighting or other interventions. The dwelling data layer was buffered by 3.3m and then the merged patches were buffered back by 3.3m, to the original extent of the outermost dwellings (Figure 3.2). This created alarmingly big patches and is perhaps key to understanding how informal settlement fires can spread to thousands of dwellings. The largest resultant patches cover areas in excess of 9 hectares (90,000m^2).



(a) (b)

Figure 3.2 - Example of (a) Dwellings and (b) their Corresponding 'Critical' Patches

The size of critical patches within a settlement is a feature of pathways for fire spread as it partly governs the extent to which a fire can grow. The risk associated with this can be quantified with respect to the weighted average of critical patch size which is calculated as:

$$A_{av} = \frac{\sum_{i=1}^{n} A_{p,i}^2}{\sum_{i=1}^{n} A_{p,i}}$$

With,

A_{av} weighted average critical patch size (m^2),

$A_{p,i}$ area of any given patch within a settlement that has n patches.

A larger patch size not only means a greater extent to which a fire in that patch would be able to travel, but also the higher the probability that the average fire would be initially located in that patch (assuming the probability of ignition in any given dwelling is equal). A simple mean may grossly underestimate the risk attributable by patch size. For example, the settlement area named *Monwabisi Park B* has one critical patch of 91,600 m^2 but also many isolated dwellings, resulting in a weighted average area of 71,000m^2 but a simple mean area of only 138m^2. This relatively tiny mean is clearly not reflective of the extent through which a fire could burn in the largest patch. Thus, the weighted average was preferred.

Therefore,

$$Risk \propto P_f$$

$$P_f \propto A_{av}$$

$$X_A = \frac{A_{av}}{A_{av,max}}$$

$$X_A = \frac{A_{av}}{71000}$$

With,

A_{av} weighted average critical patch area (m^2), $A_{av,max} = 71001$,

X_A scaled relative risk attributable to critical patch area.

3.5 Moisture

It is expected that atmospheric conditions play a role in the spread of fire – specifically on the moisture present, either in or on the fuel. However, this can quickly become a very complex problem to solve, as the moisture present depends on evaporation which, in turn, varies with temperature, air flow, humidity, rainfall and atmospheric pressure. There is also the additional complexity of the variability of climate conditions in time, as seasons and weather patterns change. Accommodating this was deemed excessive for a risk-scoring model that is largely concerned with the built environment, particularly given a dearth of studies on the role of atmospheric conditions on the materials in informal settlements. Nevertheless, the role of moisture cannot be neglected when considering the mechanisms and processes of combustion. It is again necessary to draw comparisons with studies concerning wildfires. The spread of wildfire has been modelled with varying fuel moisture content, showing that, at the simplest level, a higher moisture content reduces the rate of spread, decay time and gas temperatures of a fire (Morvan, 2013). This model concerned the moisture content of vegetation beds, so it is impossible to apply any observed trends directly to informal building materials, but the basic principles should still be relevant.

For the sake of simplicity, moisture in the context of this study is taken to be determined by rainfall and temperature. Rather than being developed from fundamental principles it was calculated with respect to the overall probability of a settlement being dry at any given time in the year.

In the case of rainfall, it was assumed that the more rainfall a settlement experiences in a year, the less likely it is to be sufficiently dry to aid the spread of fire. It must be an inverse linear relationship given that more rain increases moisture and so reduces fire risk. Again, the scale of risk was determined with respect to the maximum value across all the settlements. As per the ArcPro analysis, the greatest level of rain experienced by any of the settlement areas is 1208 mm annually.

Therefore,

$$Risk \propto v_f$$

$$v_f \propto R$$

$$X_R = 1 - \frac{R}{R_{max}}$$

$$X_R = \frac{1208 - R}{1208}$$

With,

R annual rainfall (mm), $R_{max} = 1208$,

X_R scaled relative risk attributable to rainfall.

Similar to rainfall, the effects of temperature are simplified as having linear relationship with risk. However, unlike with rainfall there is initially no obvious point of zero risk. It is improbable but not impossible that a settlement can experience zero rain, so is objectively the driest a settlement can be. However, on any temperature scale, zero degrees cannot be assumed to imply no moisture. Therefore, a temperature scale must be completely relative across Cape Town's informal settlements, with the zero value simply being the temperature experienced by the coldest settlement. This was calculated by finding the incremental difference in average maximum daily temperature between each settlement and the coldest (baseline) settlement for each month of the year. The differences were then averaged over the whole year, with the results being a scale of relative maximum daily temperature above the baseline. The relative hottest settlement experienced average daily temperatures of 5.28°C above the baseline (Figure 3.3), per ArcPro analysis.

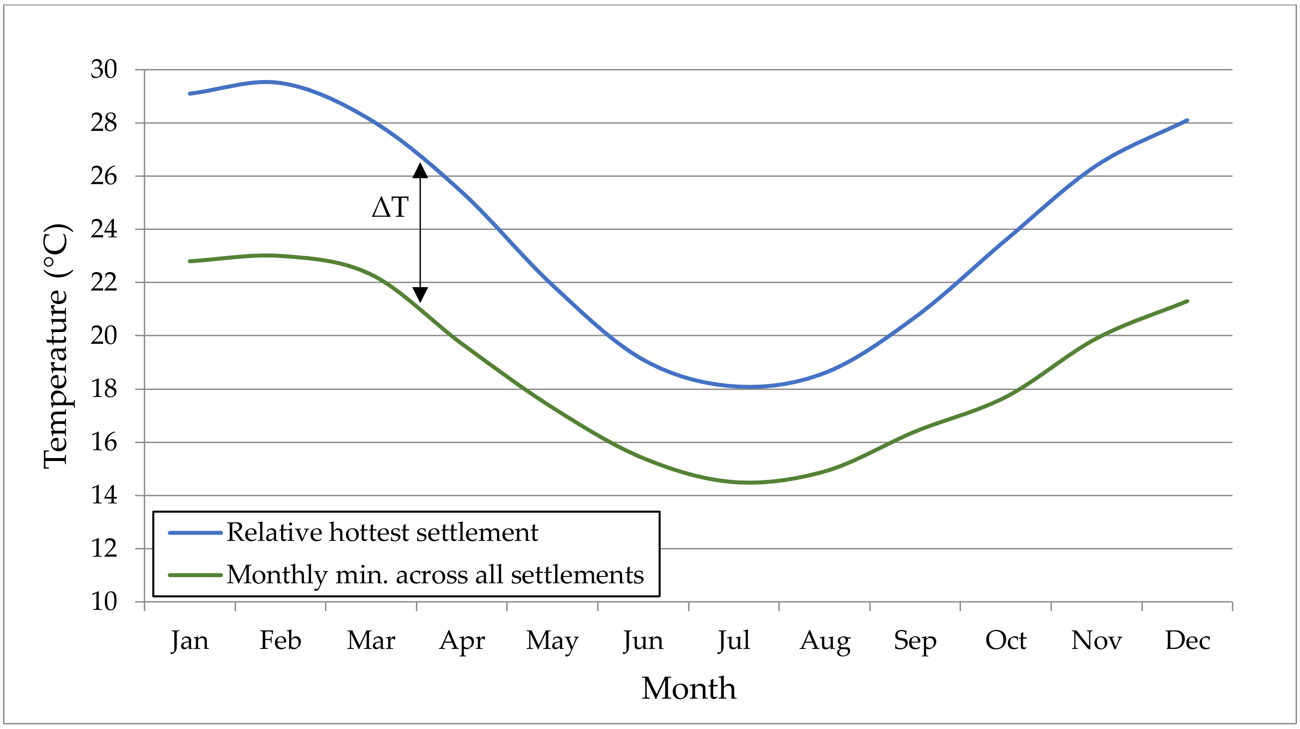


Figure 3.3 – Variation by Month of Daily Maximum Temperature Showing Hottest Relative Settlement

Therefore,

$$Risk \propto v_f$$

$$v_f \propto T_{rel}$$

$$X_T = \frac{T_{rel}}{T_{rel,max}}$$

$$X_T = \frac{T_{rel}}{5.28}$$

With,

T_{rel} relative daily maximum temperature above baseline (°C), $T_{rel,max} = 5.28$,

X_T scaled relative risk attributable to temperature.

3.6 Edge Density

Edge density is a term that is used in many fields of work with varied definitions and applications. Whilst it is a fairly well-defined concept in general GIS processing, there are few, if any, instances of it being applied in any studies relating specifically to fire. It simply means the total length of dwelling edges per area of settlement, and was calculated in ArcPro accordingly. For an area of burning dwellings, a higher edge density implies more points from which a fire can spread from, and for unburned dwellings it implies more points for the fire to spread to. In general, this can be conceptualised as a greater amount of pathways for fire to spread. It has units of m/m^2 or m^{-1}.

Edge density is a function of available pathways and is scaled relative to the settlement with the maximum edge density – which is a value of 0.63 m^{-1}.

Therefore,

$$Risk \propto P_f$$

$$P_f \propto \rho_d$$

$$X_\rho = \frac{\rho_d}{\rho_{d,max}}$$

$$X_\rho = \frac{\rho_d}{0.63}$$

With,

ρ_d	edge density (m^{-1}), $\rho_{d,max} = 0.63$,
X_ρ	scaled relative risk attributable to edge density.

3.7 Firefighting

Any possibility that a fire might be extinguished quickly depends on the response of the fire service. It is possible that residents engage in some form of firefighting activities, however this cannot be viewed as a dependable means of reducing risk.

The time of fire service response depends on the time or distance they must travel to the settlement. In South African standards, informal settlements – named as "squatter camps" by the standard – are recognised as a high risk land occupancy, so the desired response time is 8 minutes from the fire service first being notified (Standards South Africa, 2003). A delayed response is of great significance given that informal dwellings are known to burnout and collapse in as little as 2-5 minutes, increasing the chance of fire spread (Walls & Zweig, 2017). By the time the fire service first arrives, the fire may have already spread to dwellings that are two or three dwellings removed from the fire origin.

Once the fire service reaches the vicinity of a burning settlement, they must still navigate to a position from which they can engage the fire. A significant issue with informal settlements is that, though there may be road access to the settlement, there may be few or no access routes of sufficient quality within the settlement, which delays or even prevents the fire service from reaching the fire. Certainly, difficulty accessing the interior of the settlement has been noted as a pivotal factor in highly destructive fires in Cape Town (eNCA, 2017), Nairobi (BBC, 2018) and Manila (Villamor & Goldman, 2017) – fires which destroyed many thousands of dwellings in a matter of hours.

The risk associated with this can be quantified with respect to the average distance of all points in a settlement area to any formal roads. It is possible that a settlement is only accessible by informal tracks, but it cannot be guaranteed that these tracks are passable by fire engines. Furthermore, there are potentially off-road spaces available in a settlement where the fire service could assemble, but their accessibility is both difficult to verify remotely and subject to change due to the nature of the informal environment.

Of course, the fire services do not need to be able to navigate their engines directly to the base of a fire, as the hoses they use afford them some distance over which they can operate. A standard South African firefighting equipment manufacturer produces hoses of a minimum length of 15m (SafeQuip, no date). It would therefore be reasonable to expect that if a fire engine can proceed to within 15m of a fire, there is no additional risk associated with hindrance of the fire service. However, the further a fire service are from the fire, the greater the likely extent of fire spread before it is extinguished.

From ArcPro analysis, the majority of settlements are evidently accessible by formal road to at least their perimeter. However, there are two that are particularly remote from formal roads and are only accessible by informal tracks. Of these, the furthest is 436m from the nearest formal road. Whilst it is unreasonable to expect that the fire service would not attempt to make use of informal tracks to access the settlement, it cannot be guaranteed that these tracks provide the same ease of access. Thus the maximum point of risk was taken as the maximum average distance from a road for all settlement areas with road access at least to their perimeters. This is a value of 247m. The two (out of 291) settlement areas to not have roads to their perimeter were simply assigned the maximum risk score.

The average distance that the fire service can proceed on formal roads relative to any point in the settlement is taken to be a function of time with regards to fire risk. This is because any distance over which they cannot access the fire will result in the fire having to spread within their reach, or extra time taken up in which the fire service must apply extra measures to be able to access the fire.

Therefore,

$$Risk \propto t_f$$

$$t_f \propto d_r$$

$$X_{dr} = \begin{cases} 0, & d_r < 15 \\ \dfrac{d_r - 15}{232}, & 15 \leq d_r \leq 247 \\ 1, & 247 < d_r \end{cases}$$

With,

d_r average distance to formal road (m),

X_{dr} scaled relative risk attributable to distance to formal road.

The distance to fire station functions similarly to the distance to formal roads. Again, zero distance does not necessarily mean zero risk, as there is still time associated with the fire service being notified and then preparing to leave the fire station. The time between the fire starting and the fire service leaving the station must therefore be equated to an additional effective distance. It was intended that a network analysis be conducted in ArcPro to calculate travel times, however the obtained roads dataset unfortunately did not support this. Instead it was simply assumed that 1000 m of Euclidean distance represents approximately one minute of fire service travel time. It is expected that the fire service should be leaving the fire station two minutes after receiving the notification of a fire (National Fire Protection Association, 2016). The time taken for the fire service to be notified was arbitrarily assumed to be three minutes, giving a total assumed time of five minutes until the fire service leave the station. These five minutes equates to an effective travel distance of 5000 m which is added to the real distance from the nearest fire station to produce a relative scale of risk in terms of time rather than purely distance. The distance was calculated as an average distance of all points in a settlement to the nearest fire station. The maximum average distance of a settlement from the nearest fire station across all 291 settlement areas is 15,211 m, and risk is scaled relative to this.

Therefore,

$$Risk \propto t_f$$

$$t_f \propto d_s$$

$$X_{ds} = \frac{5000 + d_s}{5000 + d_{s,max}}$$

$$X_{ds} = \frac{5000 + d_s}{20211}$$

With,

d_s	average distance to fire station (m), $d_{s,max} = 15{,}211$,
X_{ds}	scaled relative risk attributable to distance to fire station.

3.8 Settlement Slenderness

The slenderness of a settlement is not a concept found in literature; it is merely an observation of how the shape of a settlement may influence the outcome of a fire. As an illustration, consider the propagation of a fire front through two quadrilaterals of equal area but different perimeter lengths (Figure 3.4). Assumptions are made that the spread velocity is equal in all directions, spread is halted at the boundary of the shape and the boundary does not influence the spread velocity once it is reached. Fire spread is essentially radial until coinciding with the shape boundary. If the fire starts at the centroid of each shape, the observed fire spread would clearly be impinged earlier for the shape of greater perimeter.

The basic concept behind this is that for shapes of greater area to perimeter ratios, the average hypothetical fire will cover a greater area before being stopped at the boundary. Whilst real settlements are not such well-defined shapes, and fire spread is almost never radial, the theory still applies. The slenderer a settlement, the greater the likelihood that a fire will spread to, and be halted at, the settlement boundary in at least one direction.

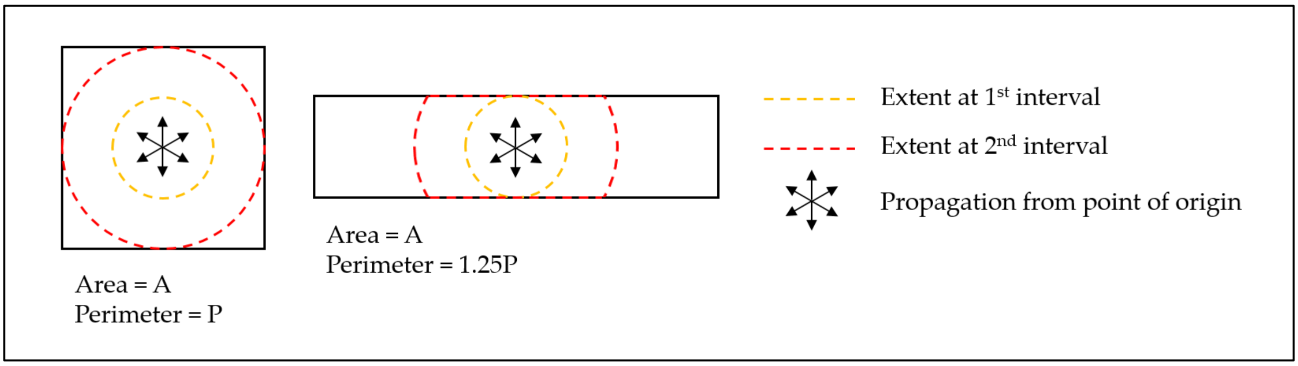


Figure 3.4 - Illustration of Settlement Slenderness

For the purpose of modelling, a settlement slenderness coefficient (Sl) was calculated in ArcPro for each settlement area as:

$$Sl = \frac{Perimeter\ length}{Area}$$

The higher the slenderness coefficient, the slenderer the settlement and the lower the risk attributable to the shape of the settlement.

There are other metrics that could quantify this concept – for example, the average distance of all points in a settlement area to the settlement boundary or centroid. However ArcPro does not have the ability to perform these calculations easily across the whole dataset, without doing it manually. Therefore, slenderness coefficient was used to simplify the process instead of conducting manual calculations for all 291 settlement areas.

Slenderness is a function of available pathways, and is scaled inversely relative to the settlement with the lowest slenderness coefficient – which is a value of 0.0083 m^{-1}. This is the only factor scaled relative to a minimum value, simply because lower slenderness implies higher risk.

Therefore,

$$Risk \propto P_f$$

$$P_f \propto \frac{1}{Sl}$$

$$X_{Sl} = \frac{Sl_{min}}{Sl}$$

$$X_{Sl} = \frac{0.0083}{Sl}$$

With,

Sl	slenderness coefficient (m^{-1}), $Sl_{min} = 0.0083$,
X_{Sl}	scaled relative risk attributable to settlement slenderness.

3.9 Neglected Factors

3.9.1 Fire Hydrants

The location of fire hydrants around and within a settlement contribute to the efficiency and time with which the fire service can engage the fire. It was initially intended that a fire hydrants dataset be included, but the attempts to obtain this data were unsuccessful. It is difficult to establish what error, if any, this will cause within a risk model. The Western Cape Government (2016) states that it operates water tankers to carry water to fires if they are no available hydrants, so it is highly unlikely that a scenario arises in which there is no possible access to water. To attempt to encapsulate the probability of this within a scoring model would be unnecessarily complex.

3.9.2 Settlement Density

The only identified study of the role of settlement density on fire spread is the work of Smith (2005) concerning past fires in the Joe Slovo and Imizamo Yethu settlements in Cape Town. Smith concluded there was some positive relationship between the number of dwellings per area and the total number of dwellings destroyed in a fire, but the correlation was weak. However, quantification of density on a dwellings-per-area basis does not lend itself well to a physical risk quantification as it gives no implicit indication of the size or spacing of the dwellings, which are significant factors when considering mechanisms of fire spread. A single past risk study was identified which explicitly considered the role of settlement density in terms of building ground coverage – a more appropriate quantifier for physical risk – but with no clear identification of the relationship between density and fire spread risk (Lao Urban Research Institute, 2004).

The complexity of settlement density lies with its multi-faceted role on fire spread. Not only does it indicate how much fuel there is in a given area, but it may also implicitly indicate the layout – proximity and spacing – of dwellings relative to one another. In actual fact, it is just a general summariser of a variety of other metrics which each influence a single aspect of fire spread. These are the aforementioned 'dwelling spacing' which influences rate of spread, and 'critical patch size' and 'edge density' which influence fire spread pathways. Incorporating these factors is a more nuanced way of encapsulating settlement density in a risk model. Therefore, it was elected to not include settlement density as a factor in the model. However, it could potentially be used in future models where a lower resolution of imagery or lack of digitised settlement plans means that these other metric datasets cannot be produced, as is discussed in 5.5.

3.9.3 Fuel

Clearly, a critical factor in determining the outcome of a fire is the properties of the fuel that is actually burning. However, quantifying this remotely across hundreds of individual settlements is a significant task and no such datasets currently exist. In attempts to establish likely fuel loads inside South African informal settlements it was concluded that an average fuel load within an informal dwelling may be 410MJ/m^2 though it was such a concentrated study that it is difficult to apply this number universally with confidence (Maree, 2015). Fuel loads may even increase to 1000-2000MJ/m^2 if the occupants store items such as firewood, tyres or paraffin for sale (Walls, et al., 2017). A dwelling containing any of these items would be of significant danger to others around it, were it to catch fire.

The building materials from which a dwelling is constructed also constitute fuel. Earlier it was discussed that when materials like polyurethane are present, fire may spread across gaps of up to 3.3m between dwellings, yet if all dwellings were constructed solely from other materials then this distance could be reduced. For instance, Wang et al. (2018) propose wood and cardboard have critical distances of 2.1m and 2.2m respectively, in the context of informal settlement fire.

Generally, it is expected that building materials and fuel load are highly influential in the wider scope of fire risk. Yet, quantifying their variation across settlements is difficult. It likely relies on understanding building material availability in different locations, as well as some quantification of employment and income level to determine what people may keep in their homes. Within the scope of this study, this has not been possible but the effect of the absence of fuel on the eventual risk model will be discussed in Chapter 4.2.3.

3.10 Summary

Spatial factors that contribute to fire spread were identified, though missing datasets necessitated the exclusion of fuel load, building materials and fire hydrants from the risk model. Collected datasets were processed in ArcPro to quantify the spatial environments of 291 settlement areas in Cape Town, by ten distinct factors. For each factor, a relative risk score variation was proposed, informed by relevant literature. Of these variations, four are simple linear relationships from zero to a maximum. The remaining six are more developed and shown in Appendix B for visual reference.

Chapter 4 – Spatial Factor Relative Weights

Having established the relationships between each spatial factor and fire spread risk, it was next necessary to quantify how each factor should be weighted in the risk model to evaluate total risk. This was facilitated by publishing a survey, completed by a selection of academics and professionals working as part of the IRIS-Fire project. Though small, the IRIS-Fire team likely represents the best pool of knowledge on informal settlement fires anywhere in the world, so should be an effective source of knowledge for quantifying risk. The results of the survey are subjective, but at least provided tangible data from which a weighted scoring method could be developed. In lieu of being able to conduct a regression analysis on fire history data, obtaining survey data was preferential over simply estimating relative weights of influence. Furthermore, literature concerning each spatial factor is most often specific to that single factor, so does little to inform an assessment of relative influence. The results of the survey informed the development of relative weights to be applied in the overall risk model.

4.1 IRIS-Fire Survey

The survey posed to the experts contained three questions intended to establish the participant's familiarity with fire and informal settlements, and their opinions on the relative influence of spatial factors to fire spread. The full survey is given in Appendix C but following is a summary and discussion of each question, outlining the intention behind the question and what it was hoped to achieve. Participants were also given a help sheet which outlined the intended definitions of the spatial factors (Appendix D).

Question 1 – Primary field of expertise

Participants were asked the field of expertise in which they have most knowledge and understanding as a professional. Given the complex socio-physical context of informal settlements, the range of potential participants was diverse, and included engineers, fire scientists, geographers and social scientists. Across these fields there is likely a wide variation in the understanding of the fundamentals of fire behaviour and so it was expected that the results would vary across respondents. The overall results of the survey could be corrected to account for any significant outlying responses if these were judged to be due to a gap in professional knowledge.

Question 2 – Informal settlement experience

Participants were asked if they have ever visited an informal settlement. If they have, they were deemed more likely to mentally grasp the physical environment of a settlement, and its role in fire spread. Again, this information could be used to inform a correction of the overall results if necessary.

Question 3 – Scoring spatial factors

Participants were asked to score spatial factors from 0-10 with respect to the influence they deem the factor to have on fire spread. A score of 10 means extremely high influence, and 0 means no influence. A scenario was posed in which an informal dwelling has ignited and become fully involved in a fire. This was so participants were dissuaded from thinking about the spatial factors in the context of ignition and would focus solely on fire spread. The collated results could be used to inform the weighting of spatial factors within the risk model.

The spatial factors listed in the survey included building materials, fuel load within dwellings and proximity to fire hydrants, in addition to the ten other factors. Whilst it was not possible to quantify spatial variability of fuel load, it is desirable to understand how the quantification of risk is affected by its omission. Proximity to fire hydrants was included because, at the stage of work at which the survey was released, it was still hoped that a fire hydrants dataset may yet have been obtained.

4.1.1 Survey Results

The survey garnered a total of ten responses across experts in the fields of fire science, civil engineering and international development. The full results are extensive so are given in Appendix E, but a summary of how the factors were scored is given in Table 4.1.

Table 4.1 - Survey Results Summary

	Factor score (0-10)												
	Dwelling spacing	**Settlement slenderness**	**Critical patch size**	**Edge density**	**Building materials**	**Fuel load**	**Proximity to accessible roads**	**Proximity to fire hydrants**	**Proximity to fire stations**	**Average wind speed**	**Annual rainfall**	**Topography**	**Daily maximum temperature**
Mean	9.5	4.6	7.5	5.7	9.0	7.8	4.9	4.6	5.0	8.0	4.4	5.8	4.8
Standard deviation	0.67	1.43	1.43	1.35	1	1.78	2.43	2.76	2.86	1.67	2.15	2.04	2.48
Median	10.0	5.0	7.0	5.0	9.0	8.0	5.0	5.0	6.0	6.0	4.0	7.0	5.5

4.1.2 Survey Analysis

Analysing the results of the survey was not an exact science. There were many levels of subjectivity to contend with, from each individual participant's interpretation of the questions, to the subjectivity of error introduced by the participant's field of expertise and experience with informal settlements. The following details the corrections that were made to the survey data and justifications for these corrections.

Correcting for Participant Variance

Of the ten participants, five were from the field of fire science and dynamics, four were from civil or structural engineering backgrounds, and one worked in international development. Qualitatively, it was expected that those who are from the field of fire science and dynamics are best informed to give meaningful responses, given their knowledge of the fundamental mechanisms of fire spread. Generally, there was a good degree of agreeability between participants, tending to favour dwelling spacing, building materials and wind speed as the most influential factors of risk. By averaging the absolute difference between each factor score given by a participant and the average score for the same factor across all participants, the degree by which each participant varied from the 'consensus' was calculated (Table 4.2). Whilst the bulk of participants gave scores which varied by around 1-1.7 points on average, Participants 05 and 08 gave scores varying by almost 2.3 points per spatial factor.

Table 4.2 - Participant Score Variance

Participant	**01**	**02**	**03**	**04**	**05**	**06**	**07**	**08**	**09**	**10**
Field of expertise*	FSD	CSE	FSD	CSE	FSD	FSD	CSE	ID	FSD	CSE
Average score variance from 'consensus'	1.32	1.34	1.68	1.60	2.26	1.06	1.23	2.26	1.40	1.38

*FSD – fire science and dynamics, CSE – civil/structural engineering, ID – international development

Participant 08 estimates the role of infrastructure as being significant in informal settlement fire risk, giving each of proximity to fire stations, accessible roads and fire hydrants a score of 9 – scores of 4.1, 4.4 and 4.0 above average, respectively (Figure 4.1). Participant 08 also gave scores of 4 for wind speed and 2 for topography, which is 4 and 3.8 below average respectively. This participant was the only respondent from the field of international development. It is possible they may not be well-acquainted with principles of fire spread at the fundamental level, and are more familiar with (and possibly overestimate) the role of infrastructure.

It was deemed justifiable to neglect the response of Participant 08, given their significant discrepancy in scoring of the spatial factors as discussed. It is understandable how a background in the field of international development may have influenced the participant's favouring of infrastructural factors, but since this is the only response in the international development 'subset', it is impossible to verify if this represents a wider base of well-founded knowledge. Certainly, the opinions of an individual cannot be assumed to reflect the view of an entire field. Hence, Participant 08's response was discounted from further use in the risk-scoring model.

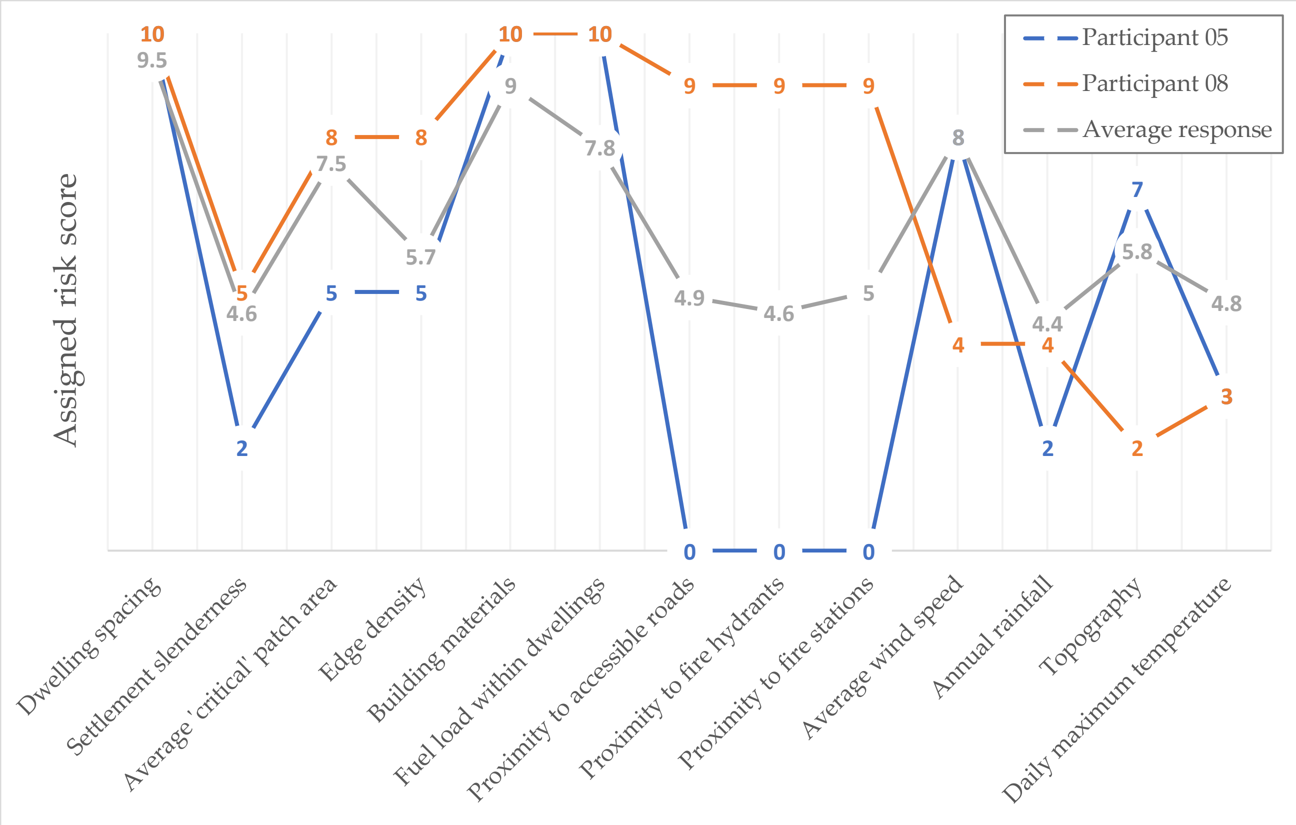


Figure 4.1 - Variation of Risk Scores for Anomalous Responses

In contrast, Participant 05 appears to significantly underestimate the role of infrastructure compared with the average response, scoring each of proximity to stations, road and hydrants zero (Figure 4.1). However, in this case it is much harder to understand these discrepancies given the context of other responses. Like Participant 08, Participants 03 and 06 are also from the field of fire science and dynamics and have not visited an informal settlement. Yet they gave responses that are much more comparable to the average, placing at least some influence on infrastructural factors. Participant 05's scoring of the ten other factors was more comparable with the average response. Neglecting the three infrastructural factors, their average score variance from the 'consensus' opinion dropped to 1.49 points which is more comparable with the 1-1.7 point range exhibited by the eight 'reliable' participants. Additionally, it has been stated that the responses of those in the field of fire science and dynamics are best informed to give meaningful results. Therefore, on balance, it was deemed that removing Participant 05's response from the model development was unjustified.

Correcting for Missing Factors

As already discussed, three factors – building materials, fuel load and fire hydrants – were either non-existent or unobtainable during the course of work, and so it was necessary to exclude them from use in the risk-scoring model. The implications of this are discussed later (4.2.3).

4.2 Methods for Weighting Factors

The next step was to conceptualise how the survey results could be interpreted and converted to relative weights.

4.2.1 Standard Weighting

The first method for calculating relative weight is a simple one, by which a factor's weight is simply determined as the ratio of its mean score from the survey to the total of all survey scores. For a factor, with a mean survey score, S, the relative weight expressed as a percentage, W, is:

$$W_{factor} = 100\frac{S_{factor}}{\sum S}$$

The relative weights produced (Table 4.3) highlight that dwelling spacing, critical patch size, wind speed and topography are expected to be the most influential factors for fire risk. Each has a relative weight above the average of 10%, with dwelling spacing constituting the largest proportion – 15.74% of risk. Note, at this stage the mean scores were corrected for the removal of Participant 08's response and the three unobtainable datasets.

Here it should be noted that the median scores were also investigated for use by this method. However, there was not a distinct enough difference between the eventual risk models developed from the mean and median values to facilitate any meaningful discussion.

Table 4.3 - Standard Relative Weights

	Factor										
	Dwelling spacing	**Settlement slenderness**	**Critical patch size**	**Edge density**	**Proximity to accessible roads**	**Proximity to fire stations**	**Average wind speed**	**Annual rainfall**	**Topography**	**Daily maximum temperature**	**Sum**
Mean score, S	9.44	4.56	7.44	5.44	4.44	4.56	8.44	4.44	6.22	5.00	60
Relative weight, W (%)	15.74	7.59	12.41	9.07	7.41	7.59	14.07	7.41	10.37	8.33	100

4.2.2 Pairwise Weighting

The second method for producing relative weights is pairwise comparison. This was a method identified across several risk studies of different types of national disaster (1.3.3). In theory, this method should only be applicable had the survey participants been asked to directly weigh each spatial factor against every other factor, requiring a total of 78 unique comparison questions. It should not be applicable when the participants were asked to directly give a risk score. However, there is a high level of subjectivity within how participants interpreted the scoring scale. When posing the question, participants were informed a score of zero means no influence on fire risk and a score of 10 means ‘extreme’ influence. Zero or ‘no influence’ is a completely objective concept, yet the scaling of participants’ scores will have depended on what their personal idea of ‘extreme’ risk was. Indeed, the range across which participants scored factors varies significantly. For instance, Participant 04 scored all factors in the range of 5-8 points, whereas Participant 05 scored factors across the full score range of 0-10 points (Figure 4.2). Utilising a pairwise comparison should compensate for this variation in scoring range, by identifying and accentuating the effect of those factors that were consistently scored highly in any subjective interpretation of the scoring range.

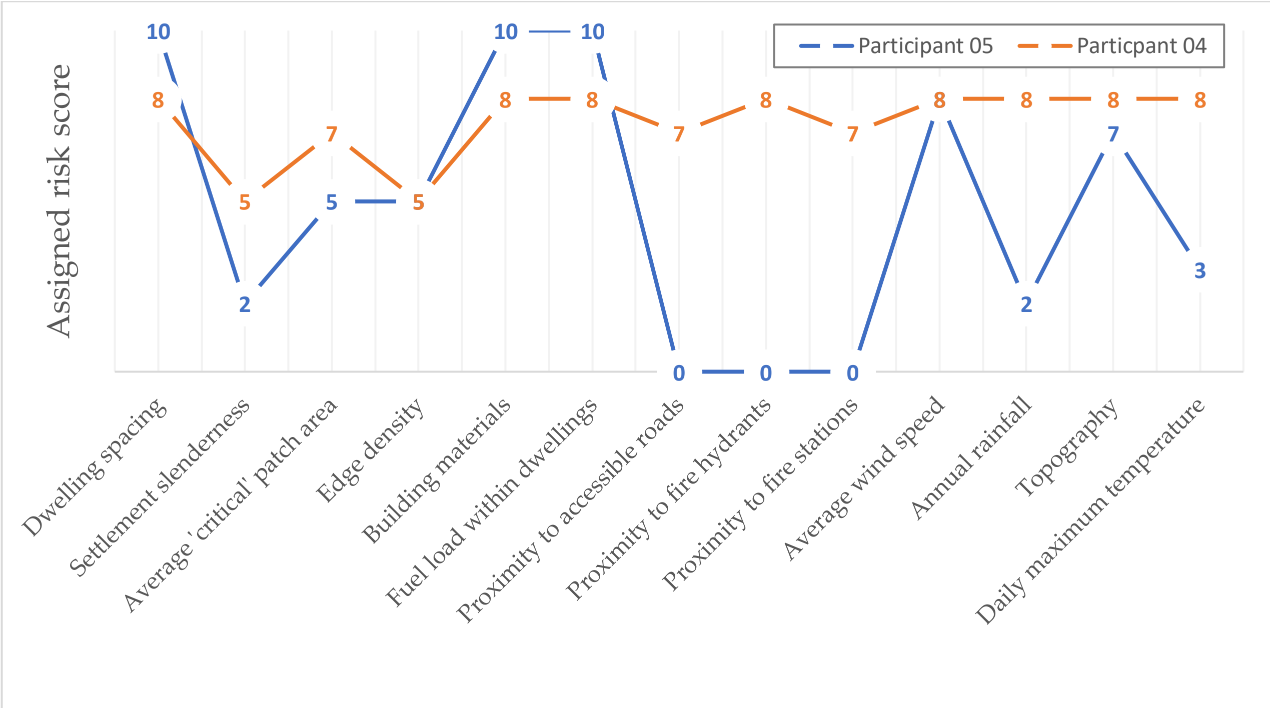


Figure 4.2 - Comparison of Participant Scoring Ranges

The method of calculation for a pairwise comparison is not particularly complex, but does rely on large matrices. The full calculation method is given in Appendix F, resulting in a set of pairwise weights (Table 4.4).

Table 4.4 - Pairwise Relative Weights

	Factor										
	Dwelling spacing	**Settlement slenderness**	**Critical patch size**	**Edge density**	**Proximity to accessible roads**	**Proximity to fire stations**	**Average wind speed**	**Annual rainfall**	**Topography**	**Daily maximum temperature**	**Sum**
Pairwise relative weight, W (%)	29.04	3.87	14.66	6.35	3.62	3.87	20.83	3.62	9.13	5.01	100

4.2.3 Errors of Missing Datasets

Datasets for building materials, fuel load and fire hydrants were not incorporated in the risk-scoring model. However, it was desirable to evaluate the potential error in the model caused as a result. Reinstating the three neglected factors, alternative relative weights were determined by the standard method (Table 4.5).

Table 4.5 – Extended Model Theoretical Relative Weights

Factor	Dwelling spacing	Settlement slenderness	Critical patch size	Edge density	Building materials	Fuel load	Proximity to accessible roads	Proximity to fire hydrants	Proximity to fire stations	Average wind speed	Annual rainfall	Topography	Daily maximum temperature	Sum
Mean score, S	9.44	4.56	7.44	5.44	8.88	7.56	4.44	4.11	4.56	8.44	4.44	6.22	5.00	80.56
Relative weight, W (%)	11.72	5.66	9.24	6.76	11.03	9.38	5.52	5.10	5.66	10.48	5.52	7.72	6.21	100

As per these results, spatial variance in building materials, fuel load and proximity to fire hydrants should account for 25.5% of a risk-scoring model. Significantly, building materials and fuel load should account for 20.4% of risk. It is, perhaps, obvious that the actual fuel – dwellings and their contents – ought to be highly influential in determining fire risk, but it is useful to quantify by what margin a proposed risk model may be incorrect due to lacking these factors. Certainly, methods for identifying and spatially quantifying fuel load should be of immediate concern for future work on this topic.

Conducting a brief second pairwise comparison, it was calculated that the total proportion missing increased to 29.7%, with the proportion attributable to the building materials and fuel load increasing to 27.5%. It is still apparent that the lack of fuel-related factors affects the accuracy of a fire risk-scoring model, but it is noteworthy that this error is increased slightly by using the pairwise weighted method.

4.3 Final Risk Model

The final step in producing an overall risk score for each settlement was to combine the relative weights with the scaled relative risks for the spatial factors (Chapter 3). The most obvious and intuitive method for doing this was to simply sum the relative risk multiplied by weight of all ten spatial factors. The model is also scaled to a 0-100 range, purely for clarity when discussing the results, giving:

$$X_{settlement} = 100(X_{Sp}W_{Sp} + X_{Sl}W_{sl} + X_A W_A + X_\rho W_\rho + X_{dr}W_{dr} + X_{ds}W_{ds} + X_w W_w + X_R W_R + X_\theta W_\theta + X_T W_T)$$

Or simply:

$$X_{settlement} = 100 \sum W_{factor} X_{factor}$$

The weightings are either standard or pairwise as per 4.2 (Table 4.6).

This method is the simplest and best reflects the style in which the survey was presented. There are other numerical methods by which risk factors can be combined to calculate the risk score, however these are best to discuss with the context of the results of this initial model.

Table 4.6 - Summary of Relative Weights

	Factor										
	Dwelling spacing	**Settlement slenderness**	**Critical patch size**	**Edge density**	**Proximity to accessible roads**	**Proximity to fire stations**	**Average wind speed**	**Annual rainfall**	**Topography**	**Daily maximum temperature**	**Sum**
Subscript	Sp	Sl	A	ϱ	dr	ds	w	R	Θ	T	
Standard relative weight, W (%)	15.74	7.59	12.41	9.07	7.41	7.59	14.07	7.41	10.37	8.33	100
Pairwise relative weight, W (%)	29.04	3.87	14.66	6.35	3.62	3.87	20.83	3.62	9.13	5.01	100

4.4 Summary

A survey was designed and published to experts associated with the IRIS-Fire project, with the results informing the development of spatial factor weights within the overall risk-scoring model. The weights were developed by two numerical methods, namely standard and pairwise weighting. Whilst there was significant subjectivity in analysing and processing the survey results, this was viewed as the best method in lieu of a direct numerical analysis of fire history data.

Chapter 5 – Results and Analysis

5.1 Risk Model Results

The full results are extensive, given there are 291 individual settlement areas to which data has been attributed. The full rankings are given in Appendix G, with the top 20 ranked settlements for each weighting method shown here, scored out of 100 (Table 5.1).

Table 5.1 - Top 20 Settlements Ranked by Risk Score

	Standard weighting			**Pairwise weighting**		
Rank	**'Settlement area' name**	**Settlement / Region**	**Risk score**	**'Settlement area' name**	**Settlement / Region**	**Risk score**
1	*Kosovo*	Philippi	59.0	*Kosovo*	Philippi	67.6
2	*Monwabisi Park B*	Monwabisi Park	57.7	*BM Section*	Khayelitsha	65.6
3	*BM Section*	Khayelitsha	56.9	*Dontshiyake*	Imizamo Yethu	65.4
4	*Doornbach*	Du Noon	56.3	*Siyahlala - Du Noon*	Du Noon	64.2
5	*Klipfontein Glebe Compact*	Philippi	55.7	*Sweet Home*	Philippi	64.0
6	*Sweet Home*	Philippi	55.5	*DT Section 1*	Khayelitsha	63.4
7	*Siyahlala - Du Noon*	Du Noon	55.0	*Wetlands*	Masiphumelele	63.0
8	*DT Section 1*	Khayelitsha	54.3	*Zululand*	Masiphumelele	61.3
9	*Dontshiyake*	Imizamo Yethu	52.9	*KTC*	Nyanga	61.2
10	*Ekuphumleni - Du Noon 3*	Du Noon	51.7	*Texas*	Hangberg	61.2
11	*Europe*	Gugulethu	51.5	*Hugenote*	Imizamo Yethu	61.0
12	*RR Section*	Khayelitsha	51.3	*Doornbach*	Du Noon	60.9
13	*KTC*	Nyanga	51.1	*Klipfontein Glebe Compact*	Philippi	60.9
14	*Monwabisi Park A*	Monwabisi Park	51.0	*BT Section*	Khayelitsha	60.8
15	*BT Section*	Khayelitsha	50.8	*Wag n' Bietjie 4*	Strand	60.5
16	*Area K*	Philippi	50.8	*Area K*	Philippi	60.4
17	*Phola Park - Philippi*	Philippi	50.7	*Block 6*	Philippi	60.3

18	*Wag n' Bietjie 4*	Strand	50.7	*Phola Park - Philippi*	Philippi	60.1
19	*Wetlands*	Masiphumelele	50.6	*Lotus*	Philippi	59.8
20	*Fisantekraal*	Fisantekraal	50.4	*Unknown 1 near Wag N Bietjie*	Strand	59.7

The standard weighting method produced a risk score variation of 22.0-59.0 with an average of 42.2, whereas the pairwise method produced a variation of 20.0-67.6 with an average of 48.9. The risk distributions share a similar shape when sorting settlements by rank from 1-291, but the standard method covers a smaller range of scores (Figure 5.1).

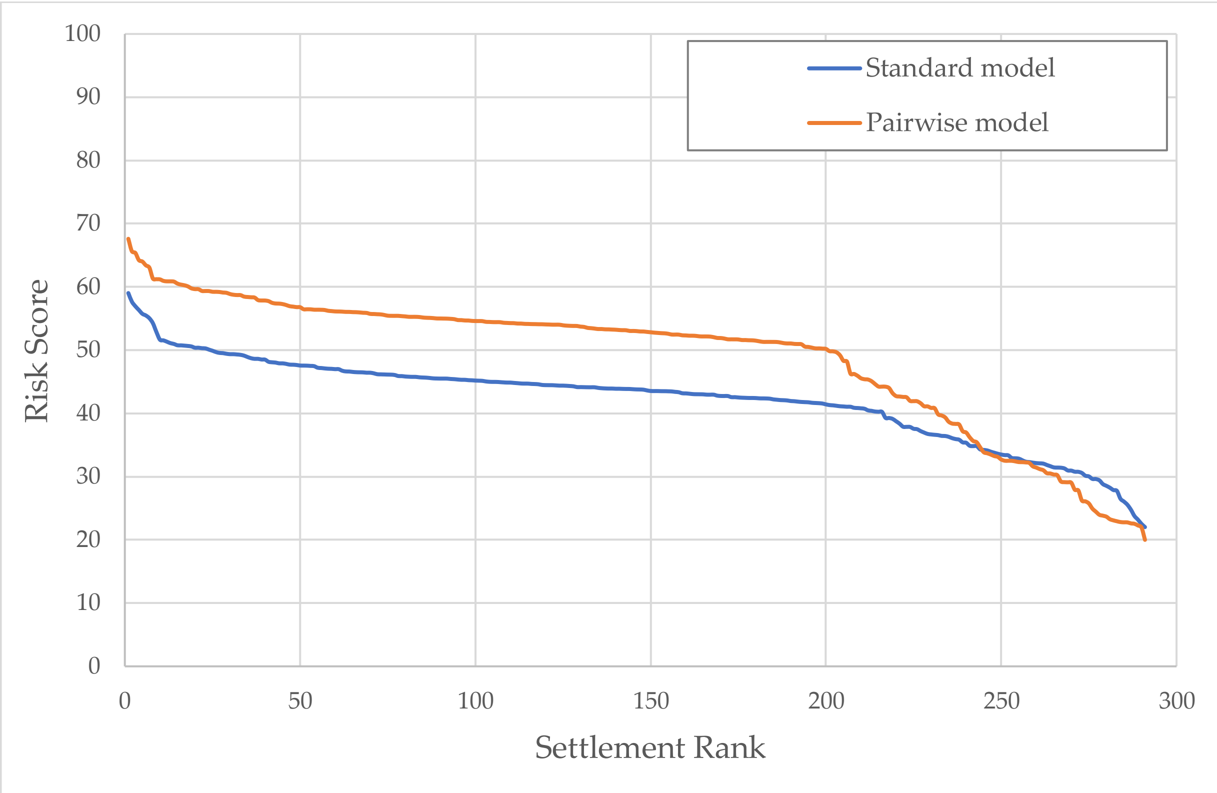


Figure 5.1 - Risk Score Distribution of Standard and Pairwise Risk Models

5.2 Fire History Data Limitations

It was previously established that fire history data can be of use as a metric of comparison for a risk model. However, prior to making comparisons between the proposed risk models and fire history, it is worth discussing the extensive limitations of the available fire history data.

5.2.1 Unit of Analysis

By overlaying the settlement boundary dataset on the fire history dataset, it can be observed that many of the fire history grid squares contain all or parts of multiple different settlement areas (Figure 5.2). Hence, it was difficult to make direct comparisons between a settlement's fire risk score and the fire history data, unless it is quite clearly the only settlement in a grid square.

Had the fire history data been attributed and mapped to the specific settlements rather than in a generic grid distribution, it may have been possible to perform a regression analysis of the spatial factors. This would allow for the production of a weighted risk scoring model directly from the fire history data, rather than having to develop a model independently and subsequently making manual comparisons.

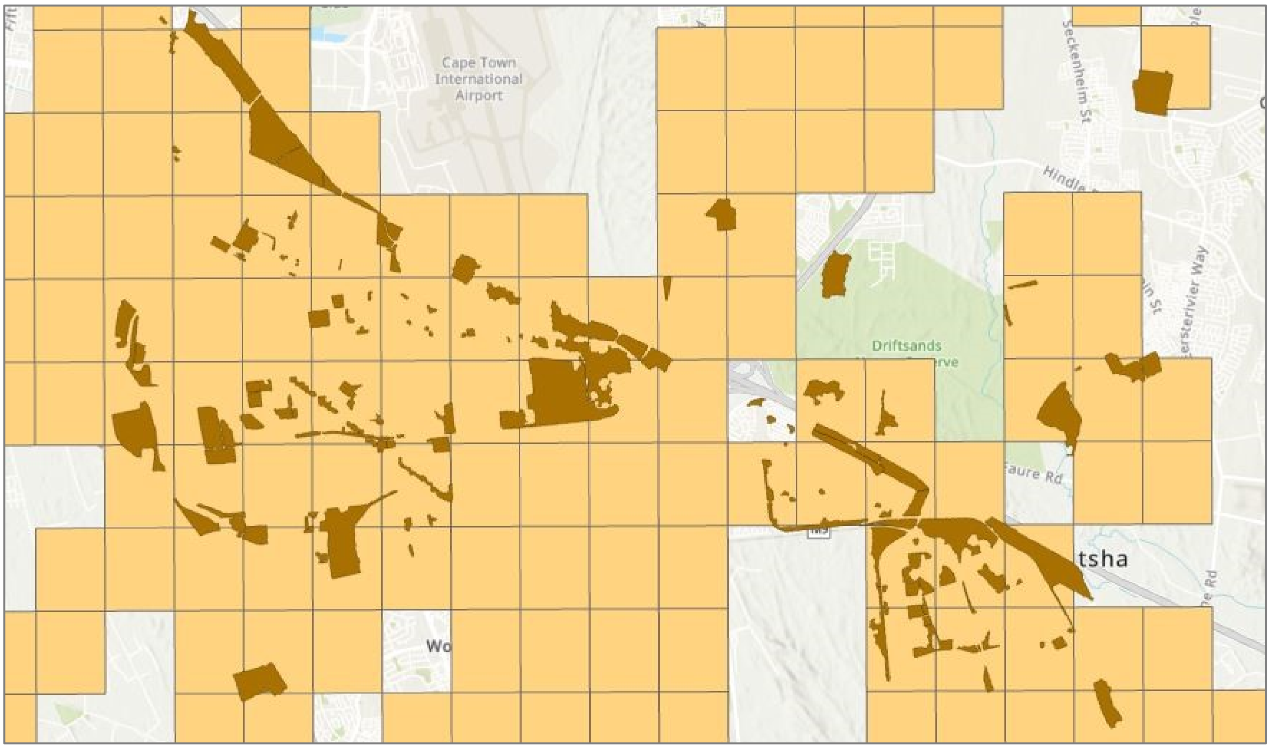


Figure 5.2 - Units of Analysis: Settlement Areas Dataset Overlaying Fire History Data Grid

5.2.2 Settlement History

A further limitation of the data is that is only spans a period of six years, from 2009-2015. One issue with this is that the settlement and dwelling datasets used to quantify the various spatial factors are up to date. Thus, there is the possibility that settlements have grown or changed since the fire history data was collected and so the current settlement does not accurately reflect past vulnerability to fire. Furthermore, there is even the possibility that settlements did not exist at the time that fire history data started being collected. As a brief example, consider the Klipfontein Glebe informal settlement which is now one of the largest settlements by area at 47.7 ha, but in 2010 was an empty wasteland (Figures Figure 5.3, Figure 5.4). In some instances, there are settlements that are not spatially incident with any fire history data, potentially because they were also not yet in existence during the period of data collection.

Figure 5.3 - View Eastward along Sheffield Road, Cape Town, Dated 2017 (Google Maps, 2019)

Figure 5.4 - View Eastward along Sheffield Road, Cape Town, Dated 2010 (Google Maps, 2019)

5.2.3 Informal Dwelling Typology

A final limitation of the fire history data is the fact that it includes records of fires for any informal dwelling. That can include those that are standalone dwellings or are in areas of mixed formality – hence, the occurrence of fire history data that is not spatially coincident with any informal settlements (Figure 5.2). The paradigm of fire risk is different for such dwellings, and is not within the scope of this study. Fires in standalone dwellings or in dwellings built adjacent to formal dwellings, by virtue of their position, will likely not spread to the same extent as observed in fully informal settlements. Thus, the average fire size across the whole fire history dataset is likely lower than if only informal settlement fires were considered.

5.3 Risk vs Fire History

5.3.1 Full Datasets

Prior to making any comparisons between individual settlements and fire history data, comparisons were made between the overall distributions of risk score and fire history. As such, a connection could be made between this theoretical risk, and the physical reality of the extent to which a fire may spread.

The fire history dataset contains 401 grid areas, exhibiting average fire sizes up to 71 dwellings destroyed per fire. The risk-scoring model was applied to the 291 'settlement areas'. Sorting both the fire history areas and settlement areas by rank, and normalising – simply dividing the rank by 401 and 291 respectively – it was observed that there are distinct regimes that may connect fire history to fire risk (Figure 5.5).

In the fire history dataset, the bottom 40% of areas have an average fire size of 1 dwelling per fire. This is indicative of fires that are unable to spread beyond the dwelling of origin. This 40% is likely not reflective of solely informal settlements, given the inclusion of standalone dwellings and mixed formality areas in the dataset. However, it may correlate to the bottom 30% of 'settlement areas' in both weighted risk models. Here, it is apparent the risk score drops off rapidly by settlement rank from scores of approximately 41.0 and 50.0 for standard- and pairwise-weighed models respectively.

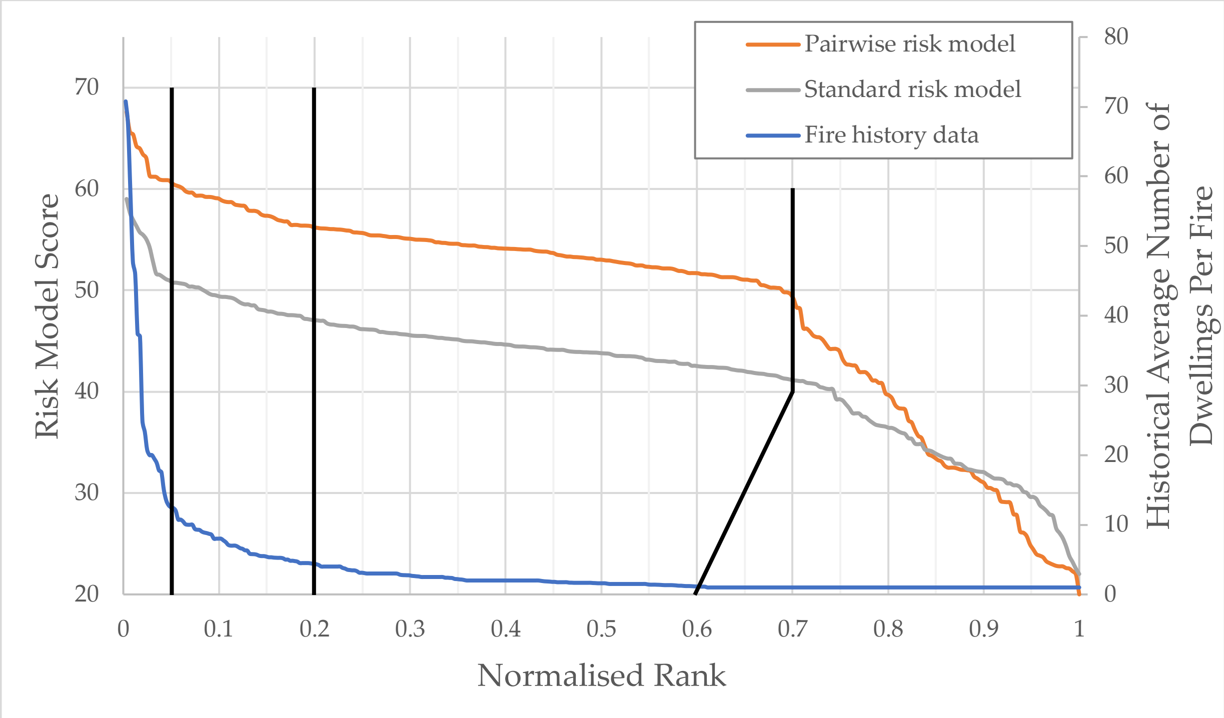


Figure 5.5 - Risk Distribution of Scoring Models and Fire History Data, (Regime Correlation Limits Marked)

By average fire size, the next 40% of areas exhibit a linear increase from 1 to 4 dwellings per fire, indicative of a fire successfully spreading, but not significantly. This may correlate to a similar linear increase exhibited by both risk scoring models across the middle 50% of settlement areas.

For both the fire history data and risk models, the top 20% of areas exhibit an exponential increase in fire size and risk score respectively. Correlating the two implies that, if a settlement scores over 47.0 in the standard model or 56.0 in the pairwise model, it is at risk of extensive fire spread. Even within this top 20% – around 60 settlement areas – it can be observed that there is a significant variation across the top few settlements. Though it is not clear exactly where this occurs, it can be approximated as the top 5%.

Making these correlations creates a basis by which risk scores and fire incidence data can be mapped and compared. Each percentile identified can be assigned as a risk category relative to score limits that applies to all three datasets (Table 5.2).

Table 5.2 - Risk Categories

Risk category	Approximate percentile	Standard model score	Pairwise model score	Average fire size
Low	70-100	≤ 41.0	≤ 47.0	= 1
Medium	20-70	≤ 47.0	≤ 56.0	≤ 4
High	5-20	≤ 51.0	≤ 60.0	≤ 12
Very high	0-5	≤ 59.0	≤ 68.0	≤ 71

5.3.2 Individual Settlements

The risk category limits were applied in ArcPro to produce visual spatial variations of risk. Making visual comparisons across 291 settlement areas and 401 fire history areas is a complex task, and a full comparison is simply unfeasible. However, there are several points of interest for comparing the accuracy of each of the two scoring models.

There are settlements for which both risk scoring models appear to reflect past vulnerability to fire. Good examples are *BM Section* in Khayelitsha and the Du Noon cluster of settlements (Figure 5.6).

However, the risk models disagree on the fire risk present in some of the settlements which have been worst affected in the past. In particular, Masiphumelele and Imizamo Yethu have experienced terrible histories of large fires. Both fall within the 'very high' category of average fire size, and that does not take in to account further fires that they have experienced since the data was collected. In the case of Imizamo Yethu, this includes a 2017 fire that destroyed over 3000 dwellings (Brandt, 2017). Yet, whilst the pairwise model correctly scores all of these settlements as 'very high' risk, the standard model partly or fully scores them in the 'high risk' category (Figure 5.7). This may not seem a significant discrepancy, but the high risk category only implies an average fire size of 12 dwellings, which is incomparable to the Imizamo Yethu fire or the 800 dwellings destroyed in the Masiphumelele fire of 2015 (Koyana & Fisher, 2015).

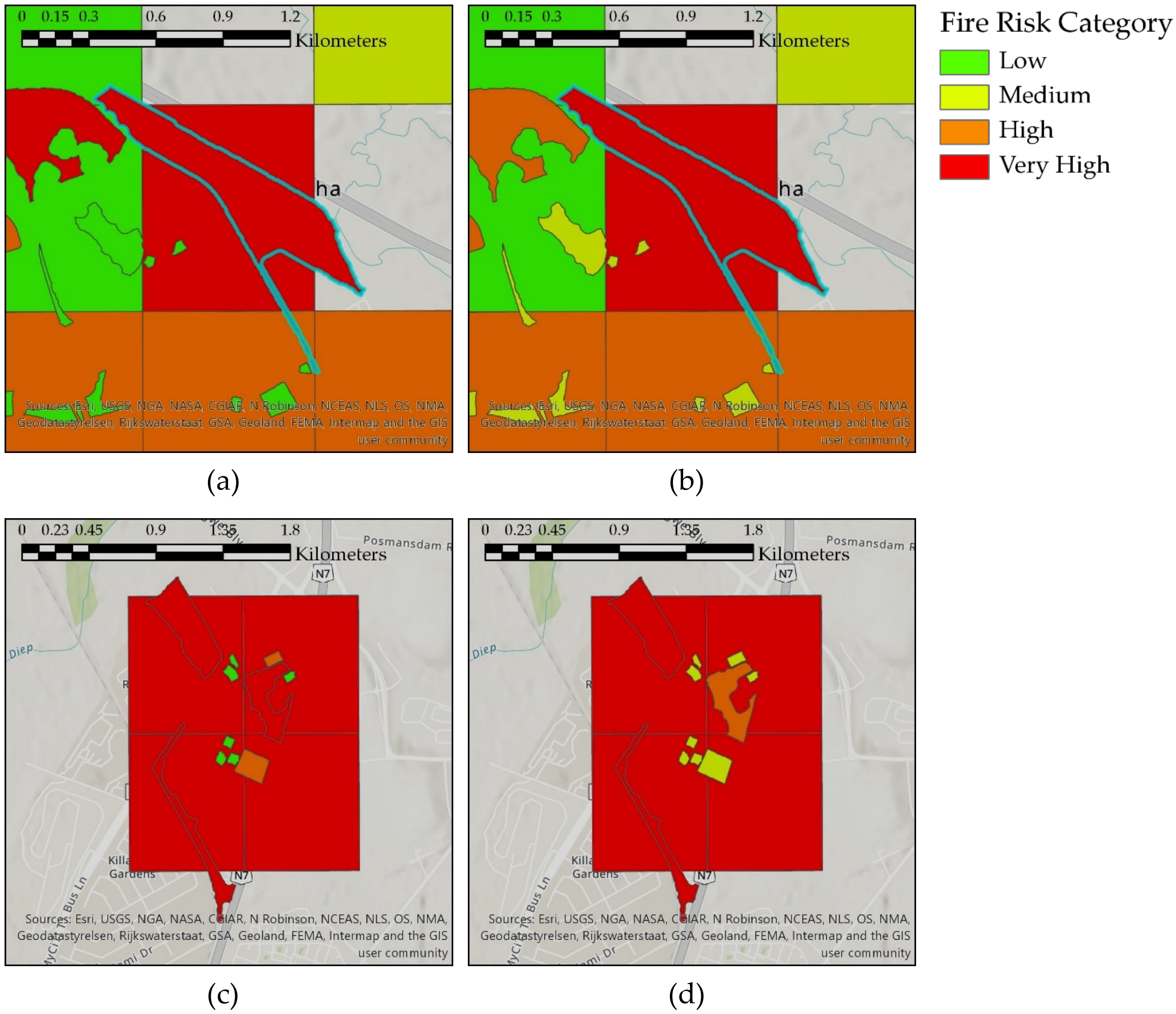


Figure 5.6 - Visual Risk Comparisons for BM Section (highlighted) by (a) Standard and (b) Pairwise models, and Du Noon Settlement Cluster by (c) Standard and (d) Pairwise Models

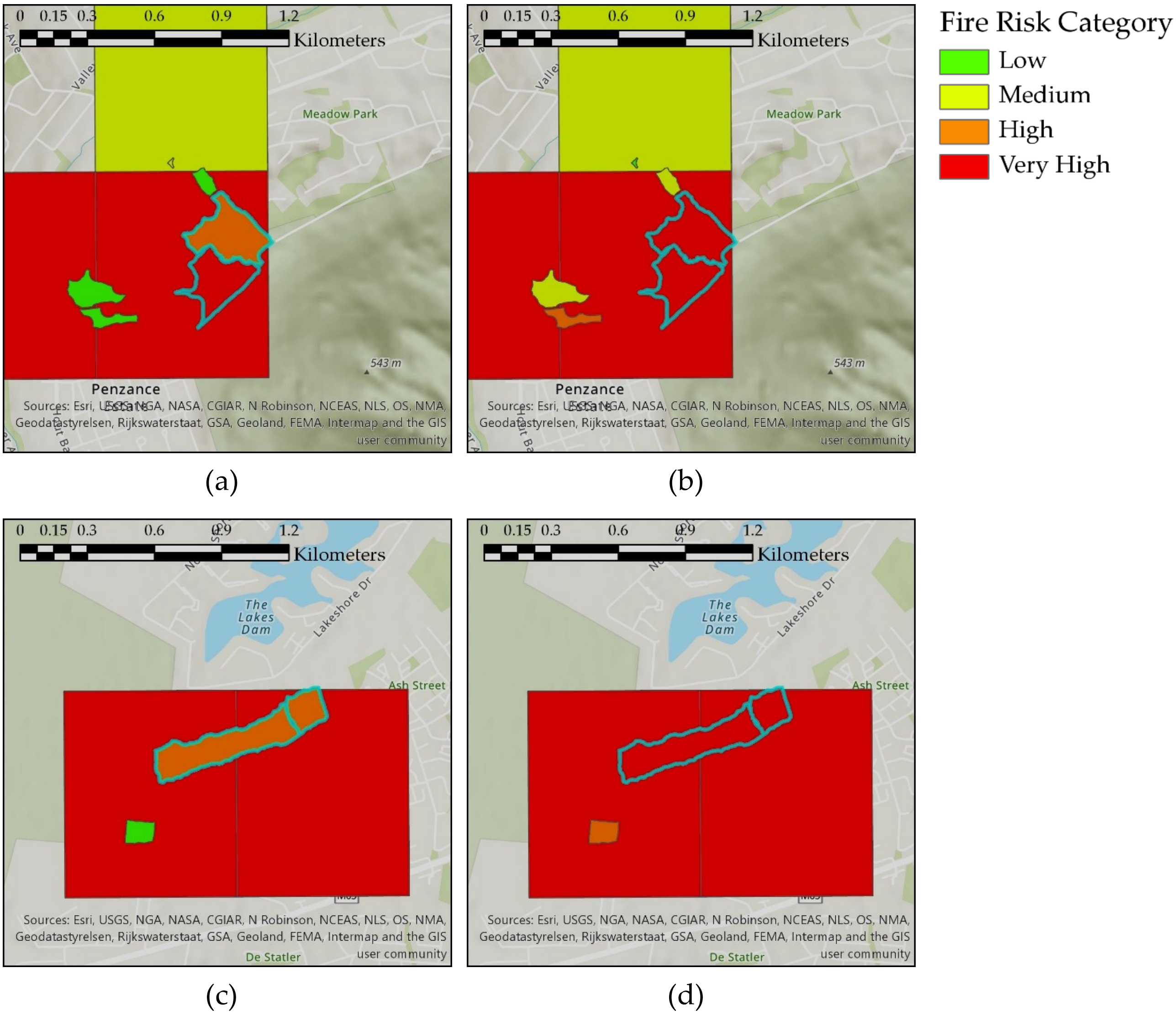
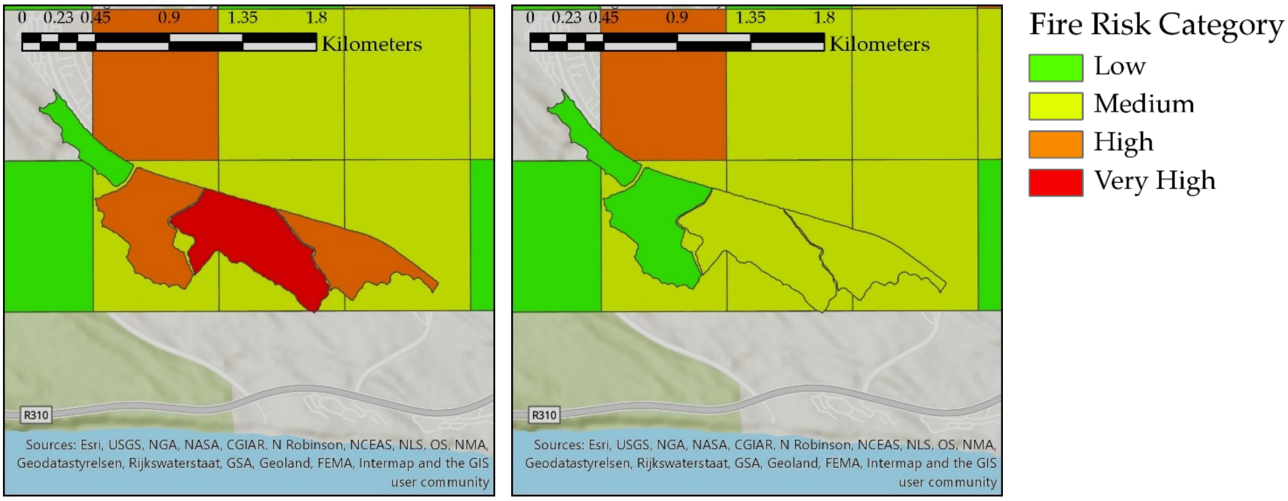


Figure 5.7 - Visual Risk Comparisons for Imizamo Yethu (highlighted) by (a) Standard and (b) Pairwise models, and Masiphumelele (highlighted) by (c) Standard and (d) Pairwise Models

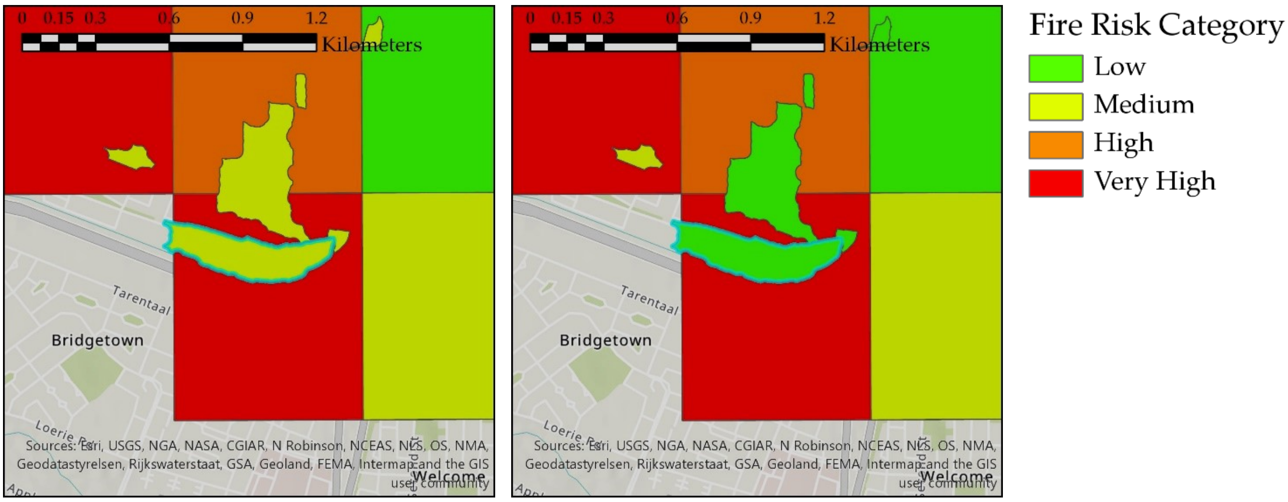
There is further evidence of error in the standard model. For example, where the pairwise model appears to identify the Monwabisi Park settlement as being of relatively low risk, the standard model scores three sections as high or very high risk (Figure 5.8). This is not consistent with fire history, given these three sections lie exclusively in areas that have an average fire size of no more than 2.4 dwellings. Ranking this settlement at the same level or higher as the likes of Masiphumelele is clearly a significant fault with the model. The standard model further ranks settlements such as *RR Section* in Khayelitsha and *Fisantekraal*, which have no particular evidence of past severe fires, as 'very high' risk.



(a) (b)

Figure 5.8 - Visual Risk Comparison for Monwabisi Park Settlement Areas by (a) Standard and (b) Pairwise Models

The pairwise model is by no means perfect. For example, neither model appears to recognise the high risk of the *Joe Slovo* settlement. If taken to correlate directly to the fire history data it overlays, *Joe Slovo* exhibits the second highest average fire size, after Masiphumelele. Yet, both models rank it as only 'low' or 'medium' risk (Figure 5.9). This may reflect a change in the layout of the settlement since the data was recorded. However, that would imply a significant drop in risk of a settlement that experienced a 60-dwelling fire as recently as 2017 (Khoza, 2017).



(a) (b)

Figure 5.9 - Visual Risk Comparison for Joe Slovo (highlighted) by (a) Standard and (b) Pairwise Models

In both risk-scoring models, the highest ranked settlement for fire risk is *Kosovo*. The three fire history grid squares it overlay suggest it is medium or high risk (Figure 5.10), with an average fire size of 8.9 dwellings at most. However, this would not appear to reflect the current conditions of a settlement which experienced separate fires that destroyed 100 dwellings in 2016 (Nkalane, 2016) and 120 dwellings in 2018 (Chiguvare, 2018).

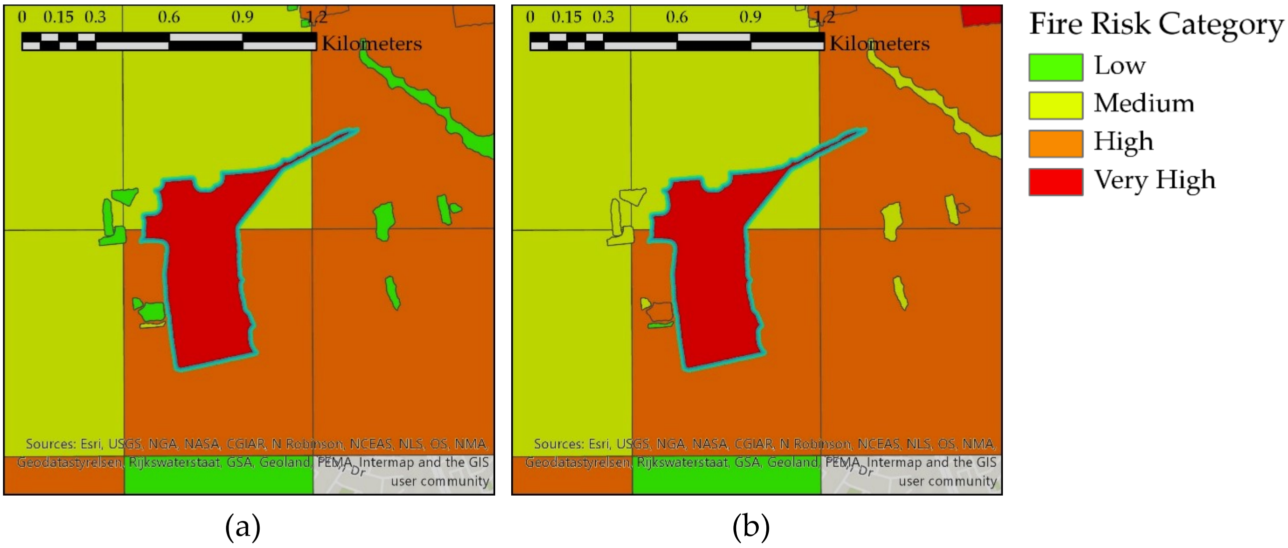


Figure 5.10 - Visual Risk Comparison for Kosovo (highlighted) by (a) Standard and (b) Pairwise Models

Generally, sound comparison between the models and the fire history is very difficult given the multitude of limitations of the fire history dataset. However, on balance it is deemed that the standard model produces more erroneous estimations of risk. Whilst the pairwise model also contains errors that must be explored further, it appears to be more accurate and consistent with fire history, and so is worth more discussion. Hereafter, all analysis of the "risk model" relates specifically to the pairwise risk model.

5.4 Risk Model Applications

Whilst a full risk-scoring model may identify the total relative risk across settlements, it does not necessarily identify exactly *why* a settlement may be at risk. This is of particular importance when it comes to introducing risk reduction measures. For example, a settlement that is vulnerable due to poor accessibility for the fire service may require completely different protective measures than a settlement that is built on a slope. By breaking the scoring model down into three distinct spatial categories – environmental, interior infrastructure and exterior infrastructure – insight can be gained into how settlements are prone to different types of vulnerability (Table 5.3). Of course, an overall risk-scoring model is still of use for identifying which settlements are most at need of immediate protection.

Table 5.3 - Factors by Spatial Category

Environmental		**Interior infrastructure**		**Exterior infrastructure**	
Spatial factor	**Pairwise relative weight (%)**	**Spatial factor**	**Pairwise relative weight (%)**	**Spatial factor**	**Pairwise relative weight (%)**
Average wind speed	20.83	Dwelling spacing	29.04	Proximity to accessible roads	3.62
Annual rainfall	3.62	Settlement slenderness	3.87	Proximity to fire station	3.87
Topography	9.13	Critical patch size	14.66		
Daily maximum temperature	5.01	Edge density	6.35		
Total weight contributed / %					
38.59		53.92		7.49	

5.4.1 Environmental Risk

Environmental factors are those which are imposed by location and environmental conditions – wind speed, rainfall, topography and temperature. These environmental factors make up 38.6% of the scoring model.

The environmental risk score of settlements was calculated simply by adding only these factors, and the rankings are largely dominated by settlements with high relative wind speed and slope angle. The top 14 ranked settlements areas include the four areas that constitute the Monwabisi Park settlement and the three areas in the Hangberg cluster. Their rankings can be compared to their rankings from the overall risk model (Table 5.4).

Table 5.4 - Select Settlements Ranked by Environmental Risk

'Settlement area' name	Part of settlement / Region	Environmental score (out of 38.6)	Environmental risk rank	Overall score (out of 100)	Overall risk rank
Hangberg	Hangberg	29.71	1	44.24	215
Texas	Hangberg	26.33	2	61.19	10
Dallas	Hangberg	24.69	6	42.60	222
Monwabisi Park M	Monwabisi Park	23.79	8	41.11	229
Monwabisi Park B	Monwabisi Park	23.15	11	54.10	118
Monwabisi Park C	Monwabisi Park	22.87	12	45.35	212
Monwabisi Park A	Monwabisi Park	22.80	14	51.06	140

With the exception of Texas, all of these settlement areas are ranked significantly lower in overall risk than environmental risk. In the case of the Hangberg, Dallas, and Monwabisi Parks M and C areas, it is particularly noteworthy that environmental risk accounts for more than half of the total risk score.

Importantly, there are settlements that may not currently be subjected to particularly high overall fire risk, but are at a disadvantage due to the environmental conditions of their location. Whilst there may be no active measures needed to protect these settlements, they should be limited from growing or densifying to prevent fire risk increasing drastically in the future.

This analysis could even be extended beyond existing settlements. Empty plots of ground could be assessed by the same method so the least desirable areas for future settlements can be established. This may help authorities to engage in the issue of informal settlements from their inception, as they could direct people where is safest to build in the long term.

Whilst this certainly would not solve the problem, it could at least provide authorities with some measure of meaningful involvement beyond forced evictions.

5.4.2 Interior Infrastructure

Factors of interior infrastructure – dwelling spacing, settlement slenderness, critical patch size and edge density – are the most influential in fire spread risk, constituting 53.9% of the overall score. They are critical to the overall layout of the fuel and passage of flame from dwelling to dwelling. Given their influence, it is proposed that understanding the roles of these factors should be a significant area for future research. As a very brief analysis, dwelling spacing encapsulates the rate of spread from any single dwelling to another; edge density, the amount of pathways for a fire to spread from a single dwelling; settlement slenderness, the inhibition of fire front development; and critical patch size, the limiting areal extent of fire spread. It is proposed that, together, these factors are crucial to understanding how fire progresses through a settlement.

The interior infrastructure risk score was calculated, summing the relevant spatial factors. Given its high relative influence in the overall risk score, it is fairly intuitive that the interior infrastructure rankings are comparable. Indeed, 31 of the top ranked settlement areas for interior risk also achieved a top 40 ranking for overall risk (though not necessarily in the same order). A detailed analysis is not as important here as the implications are less nuanced than for environmental risk. Simply, a settlement with a higher interior infrastructure risk score is more in need of immediate measures designed to prevent the spread of flame between dwellings or patches of dwellings.

5.4.3 Exterior Infrastructure

There are only two factors of risk imposed by exterior infrastructure – proximity to fire stations and accessible roads – contributing a total weight of only 7.5% to the overall risk score. These are the factors that simply determine how quickly the fire service can get to a burning settlement and begin to engage the fire.

The top two settlements ranked for exterior risk are good examples of the problems that may be imposed by wider infrastructure. *Klipheuwel* (scoring 6.08 out of 7.5) lies over 15km from the nearest fire station, and *Klein Zoute River* (scoring 5.54) is a distance of over 400m from the closest formal road. This risk constitutes only a small part of the overall risk model – *Klipheuwel* and *Klein Zoute River* rank 249th and 213th in the overall risk score rankings – yet the infrastructure available to the fire service is something over which authorities control. Adding extensions to existing roads or additional fire stations are measures that could greatly reduce fire risk in remote settlements.

Alternatively, the problem could be framed in the same manner as environmental risk. Settlements with high exterior risk but low overall risk could be targeted to prevent growth and densification whilst accepting the limitations of fire service response. Empty areas of land could also be assessed to identify those that could be at risk if built on.

The full rankings of all settlements by environmental, interior infrastructure and exterior infrastructure risk are given in Appendix G.

5.5 Density-adjusted Risk

Settlement density is crude quantifier of the more specific metrics of dwelling spacing, critical patch size and edge density (3.9.2). However, calculating these metrics for this study was aided by the fact the dwellings dataset was manually digitised. A quicker, albeit less accurate, method of remotely identifying informal settlement characteristics could incorporate automated quantification of settlement density from satellite imagery. The proposed risk model was adapted to incorporate settlement density by replacing the three factors mentioned, which make up 53.05% of the overall risk score. Settlement density was calculated in ArcPro by dividing the total area of dwellings within a settlement by the settlement area. In terms of percent ground coverage, this naturally fits on a 0 to 1 scale, as its limits are 0% and 100%.

The adjusted scoring model is therefore:

$$X_{settlement} = 100((W_{Sp} + W_A + W_\rho)X_{\rho S} + X_{Sl}W_{sl} + X_{dr}W_{dr} + X_{ds}W_{ds} + X_w W_w + X_R W_R + X_\theta W_\theta + X_T W_T)$$

$$X_{\rho S} = \frac{\rho_S}{100}$$

With,

ρ_S settlement density as percentage ground coverage (%).

There is an approximate linear relationship between the initial model scores and density-adjusted scores, but with an R^2-value of only 0.565 (Figure 5.11). If density was a feasible direct substitute, this relationship should be of the approximate form y≈x.

Figure 5.11 - Correlation of Density-adjusted Risk Model to Full Model

Comparing the rankings, it is apparent that there is a significant discrepancy between the areas of high ranked settlements. Of the top 10 settlements ranked in the initial scoring model, eight have areas from 5.3-28.1 ha. Comparatively, in the density-adjusted model, seven of the top 10 have areas of no more than 0.6 ha (Table 5.5). Additionally, the density-adjusted model ranks the top two as settlement areas which were previously not ranked in the top 100.

Table 5.5 - Comparison of Settlement Areas Between Initial and Density-adjusted Models

	Initial model		**Density-adjusted model**		
Risk score rank	**'Settlement area' name**	**Area (ha)**	**'Settlement area' name**	**Area (ha)**	**Risk score rank change**
1	*Kosovo*	27.3	*LR Section*	0.2	↑ 172
2	*BM Section*	28.1	*Sagwityi Street*	0.1	↑ 110
3	*Dontshiyake*	5.4	*YMCA 2*	1.1	↑ 40
4	*Siyahlala - Du Noon*	7.6	*Heinz Park 4*	0.1	↑ 51
5	*Sweet Home*	21.4	*KTC Training Camp 2*	0.1	↑ 71
6	*DT Section 1*	7.6	*Unknown near Wag n' Bietjie 2*	0.6	↑ 30
7	*Wetlands*	8.3	*Wetlands*	8.3	-
8	*Zululand*	2.4	*Small SBDC*	0.3	↑ 51
9	*KTC*	6.0	*Kosovo*	27.3	↓ 8
10	*Texas*	0.3	*Texas*	0.3	-

This analysis may seem irrelevant since settlement area has not been used as a metric for quantifying risk thus far. However, settlement area is partly implicative of the amount of fuel available for a fire to burn. This is covered explicitly in the initial model by critical patch size but is not something that is accounted for by solely substituting density into the model. Therefore, if a density-adjusted method is to be applied in future, there should be some kind of correction for settlement area.

5.6 Temporal Risk

Another interesting feature of the risk scoring model is the influence, or lack thereof, it attributes to variable spatial factors. The majority of spatial factors are at least semipermanent, given they do not change on a daily basis. However, wind, rain and temperature are all factors which change daily and seasonally. Summing the risk scores attributable to these variable factors, and doing the same with the seven remaining 'permanent' factors, for each settlement, variation of overall risk across all settlements is almost directly related to only non-variable factors (Figure 5.12). From the R^2-value, it is apparent that these permanent factors are responsible for 97% of the variance in overall fire risk. This is particularly surprising given that wind speed, a variable factor, accounts for almost 21% of the risk score.

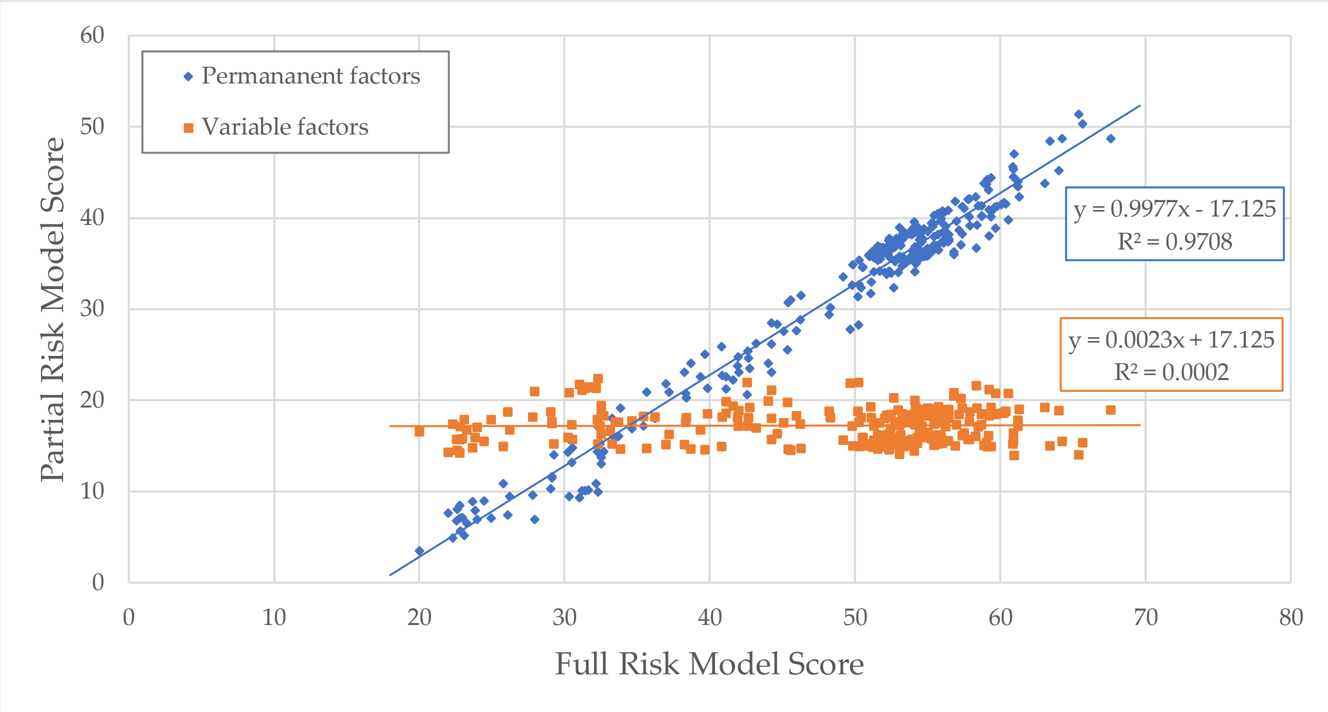


Figure 5.12 - Correlations of Overall Risk Score with Permanent and Variable Risk Factors

It is proposed that this result is an anomaly due to the methods by which the factors were initially scaled with risk. Certainly, it was complex to even attempt to conceptualise how these factors, which vary across timescales of hours and seasons, can contribute to a single objective risk score. Nevertheless, a future temporally varying risk model could be more informative regarding the best times of year to allocate resources towards different fire stations or settlements.

5.7 Multiplicative Risk

A method was also investigated for scoring risk by a multiplicative method. This was based on the theory that risk has been defined as directly proportional to the rate, time and pathways for fire spread (2.4), so an overall calculation for fire risk should really take the form:

$$X_{settlement} = \left(\sum W_{rate}X_{rate}\right) \times \left(\sum W_{time}X_{time}\right) \times \left(\sum W_{pathways}X_{pathways}\right)$$

Here, the subscripts denote any spatial factor related to that particular feature of fire spread, as outlined previously in Table 2.2.

Whilst this seems to logically follow the definitions laid out for fire spread risk, it is not necessarily compatible with the results of the survey, and the earlier methods for scaling relative risk of each factor. Certainly, preliminary investigations showed that the multiplicative method heavily favoured those settlements with large critical patch sizes. Using the pairwise factor weights, there is a good correlation between weighted critical patch size and total multiplicative risk, with a linear relationship of R^2-value 0.723 (Figure 5.13). For a scoring system dependent on ten variables, this a significant correlation. Comparatively, the factor with most theoretical influence – dwelling spacing – exhibits no obvious correlation with multiplicative risk score, with an R^2-value of 0.076 (Figure 5.13).

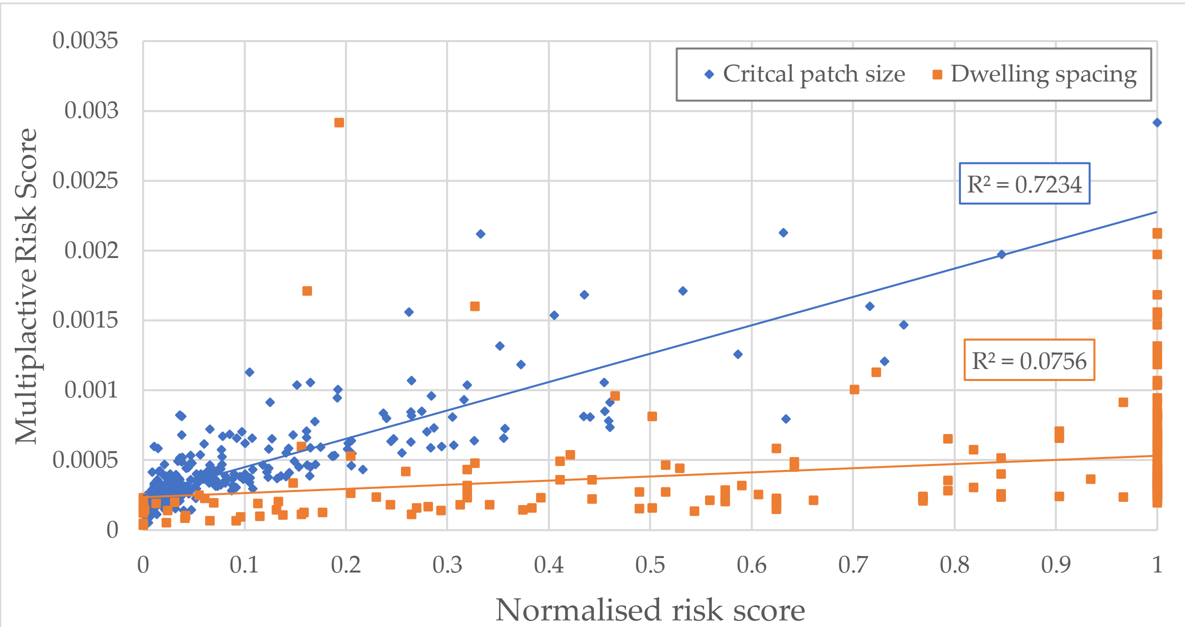


Figure 5.13 - Correlations of Critical Patch Size and Dwelling Spacing to Multiplicative Risk Score

The real implication of this is evident from the settlement rankings. For example, three of the top seven ranked settlements by multiplicative risk are three sections of Monwabisi Park which has already been noted to have no significant fire history. Furthermore, settlements known to be highly prone to large fires, such as Imizamo Yethu, dropped in the rankings. This multiplicative method should be of interest in future works as it better conceptualises the real relationship between fire spread rate and the time allowed. In the context of this study however, it was not an appropriate method of interpreting the survey results.

Chapter 6 – Conclusions

Informal settlement fires are a potential threat to the lives and livelihoods of hundreds of millions of people across the world. They are a problem that is likely to persist given the global trend of growth in these settlements. A city that has and continues to exhibit a particular vulnerability to these fires is Cape Town in South Africa. This study aimed to identify features of the spatial environment which contribute to large-scale fire spread, and quantify the risk imposed on the informal settlements of Cape Town. The wider field of spatial risk quantification and mapping was examined to discern effective ways of conceptualising and building a risk-scoring model. Past risk studies showed a variable degree of quality in quantifying risk and tended to be less effective if the concept of risk was poorly defined within the scope of that particular study. Therefore, effort was made to explicitly define what 'risk' means in the context of this study – namely, the likelihood that a fire can spread extensively across an informal settlement, neglecting ignition probability and economic vulnerability. From this, clear logical correlations were drawn between risk and individual spatial factors of a settlement. This helped to inform the development of a 'pairwise weighted' risk model, that showed some success in identifying informal settlements at very high risk of experiencing extensive fires.

6.1 Evaluating the Risk Model

The final proposed pairwise risk model was initially developed alongside a standard weighted model but was deemed to be more accurate, as it was semi-quantitatively more comparable to fire history data and other reports of fires. It successfully identified many settlements with histories of catastrophic fires, such as Masiphumelele, Imizamo Yethu and Kosovo, as 'very high' risk. However, there are clearly still errors with the model, evident particularly as it failed to identify Joe Slovo as a high risk settlement despite its history of severe fires.

Unfortunately, the comparative fire history data was fundamentally flawed for several reasons. It was mapped to a very coarse resolution relative to the informal settlements, making only semi-quantitative comparison possible. Had it been more accurate, a regression analysis may have been possible and would certainly have been desirable. Furthermore, the data was also skewed by incorporating fires in informal dwellings that were not part of a wider informal settlement. Finally, the data was limited by the relatively short time over which it was collected – six years – ending four years prior to this study. Indeed, the Klipfontein Glebe informal settlement, which was modelled as 'very high risk' in its current state, did not exist when data was first collected in 2009. On balance, it is recommended that, whilst the risk model showed a fair degree of success in identifying high risk settlements, it needs further validation by a more rigorous quantitative comparison than this data could facilitate. Future improved methods for collecting and mapping fire data would be a great benefit and would ideally attribute data to individual settlements rather than in a grid distribution.

One particular advantage of the proposed model is that it identifies the nature of each settlement's vulnerability, whether that be environmental or due to interior or exterior infrastructure. This should help to inform what protective measures are most appropriate for each settlement. In future, this analysis could also be extended to unoccupied lands to identify regions that could become high risk due to their wider environment. This provides an angle by which authorities may be engaged and take ownership of the problem of fire before it even occurs.

Part of this study also identified methods by which the model could be developed or expanded, to create more intuitive correlations between the spatial environment and fire risk. The following recommendations are proposed:

- The model should be expanded to include building materials and fuel load – since these are the actual fuel that a fire burns – to fulfil the theoretical 27.5% of total influence it is proposed they constitute within a pairwise risk model. This could be done by simply adding individual spatial factors, or potentially in combination with the 'critical patch size' factor, given its dependence on the thermal properties of building materials.

- Climatological factors were found to be only weakly influential within the overall model. This was likely due to the complexity in attempting to encapsulate their temporally-varying nature within a single objective risk score. Reconceptualising these factors may improve the quality of the model.
- The model can be adjusted if settlement density is known, but more detailed factors (edge density, critical patch size and dwelling spacing) are unknown. However, it would require some kind of correction for settlement area. This could facilitate quicker modelling as it would significantly reduce the time required for manual data processing.
- A multiplicative, rather than additive, method for quantifying risk could also be developed to more accurately quantify the fire spread rate-time relationship. This may have been an option for this study but the methodology should have been framed differently from the start to ensure it was relevant to a multiplicative model.

6.2 Future Work

In addition to corrections to the model, there is also the question of how a risk model can be of tangible use in future. It can help to identify settlements that are particularly at risk of fire but there must then be measures put in place to reduce this risk. Significant work is required to not only design physical protective measures, but also to inform policy changes that can help to influence where and how informal settlements grow from their beginning. Certainly, the provision of clear and effective risk quantification should be a motivation for authorities to at least start engaging with the issue.

The risk model highly values wind speed, dwelling spacing and critical patch size as contributors to risk. Concerning protective measures, it is recommended they are developed on the principle of inhibiting the mechanisms of fire spread controlled by these three spatial factors. It is not possible to control a settlement's exposure to wind, but measures to shelter dwellings to slow the rate of flame spread may be possible. Mitigating the effects of dwelling spacing and critical patch size should involve measures to reduce the critical distance of flame spread by changing or protecting the building materials. It could also include introducing physical barriers to flame spread.

The weakest part of the model was likely its interpretation of climatological factors and their effects on moisture and, subsequently, fire risk. Further research is required in two key areas associated with this. Firstly, work is required to establish how moisture effects the combustion of the building materials and fuels present in informal settlements. Secondly, the variation of moisture with different climatological factors – rain, wind, temperature and pressure – must be better understood. Such work could inform a more realistic method for climate-risk modelling than was achieved in this study. This would also help to develop knowledge of seasonally variable fire risk, which is currently not quantified.

It was intended that this study would also include a chapter that explored in detail the interconnectivity of factors of interior infrastructure: critical patch size, dwelling spacing and edge density. Given they are quantifiers of the layout of dwellings relative to one another, it is proposed they are crucial to overall fire spread. However, time restrictions on the study did not allow for this work to be completed.

By virtue of splitting the overall model into the three categories of environmental, interior and exterior risk, it could be easily adapted to quantify risk in empty plots of land. Neglecting factors relating to the interior of the settlement, the risk posed by the environment and wider infrastructure can be quantified. This would help to identify unfavourable areas for future settlements, allowing authorities to potentially direct the construction of new settlements, thus mitigating the issue in the long term. Adapting the model would require some slight changes in the GIS processing method.

Finally, informal settlement fires are a problem that is by no means limited to Cape Town or even South Africa, so methods should be explored to develop risk quantification methods that can be applicable to informal settlements globally. The proposed risk model may be applicable in other locations globally, but careful consideration should be made for likely differences in the prevailing climatic conditions, building materials and dwelling styles that may occur in these locations.

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Appendix A ArcGIS Pro Datasets

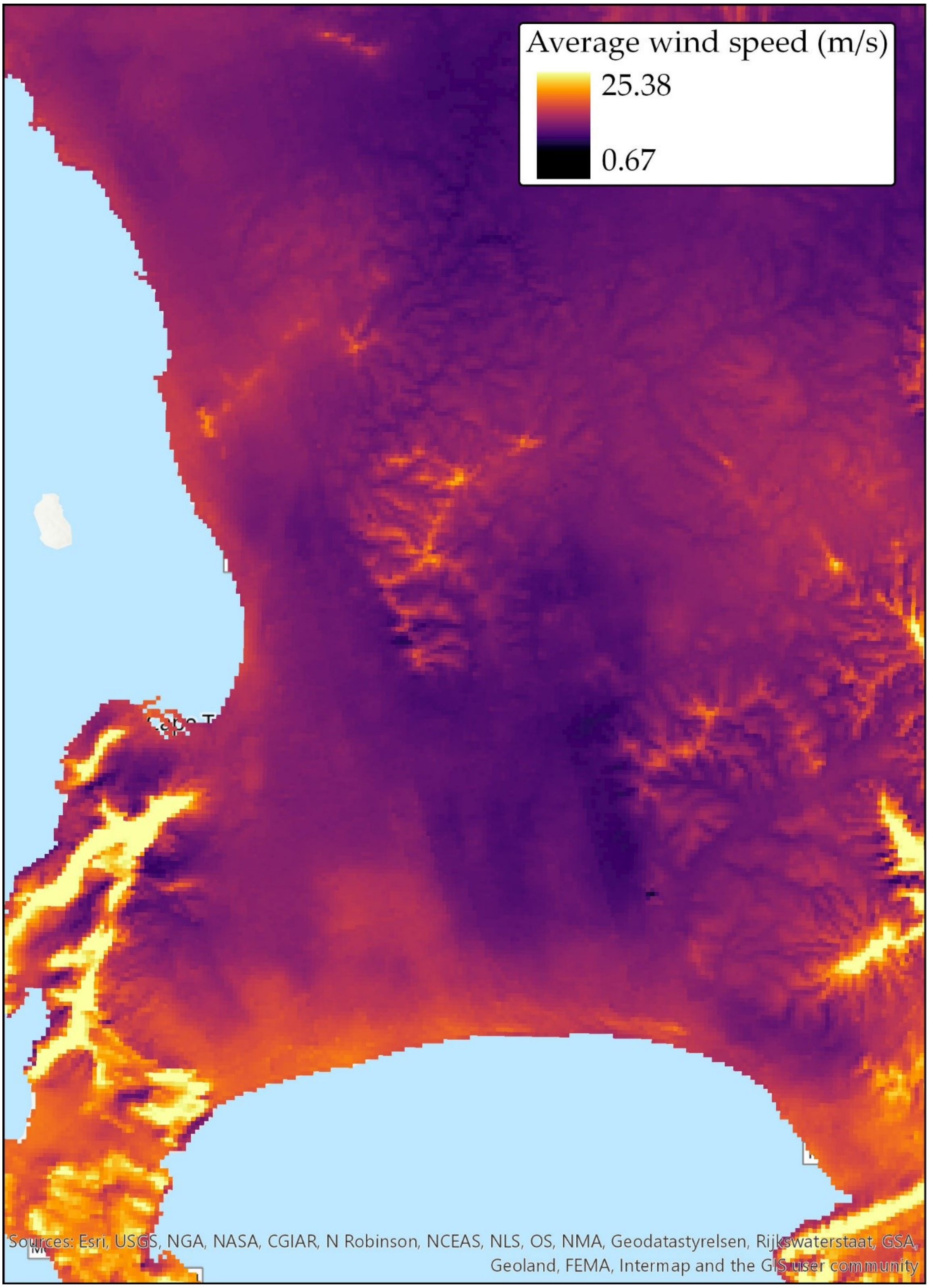


Figure A . 1 - Average Wind Speed Dataset

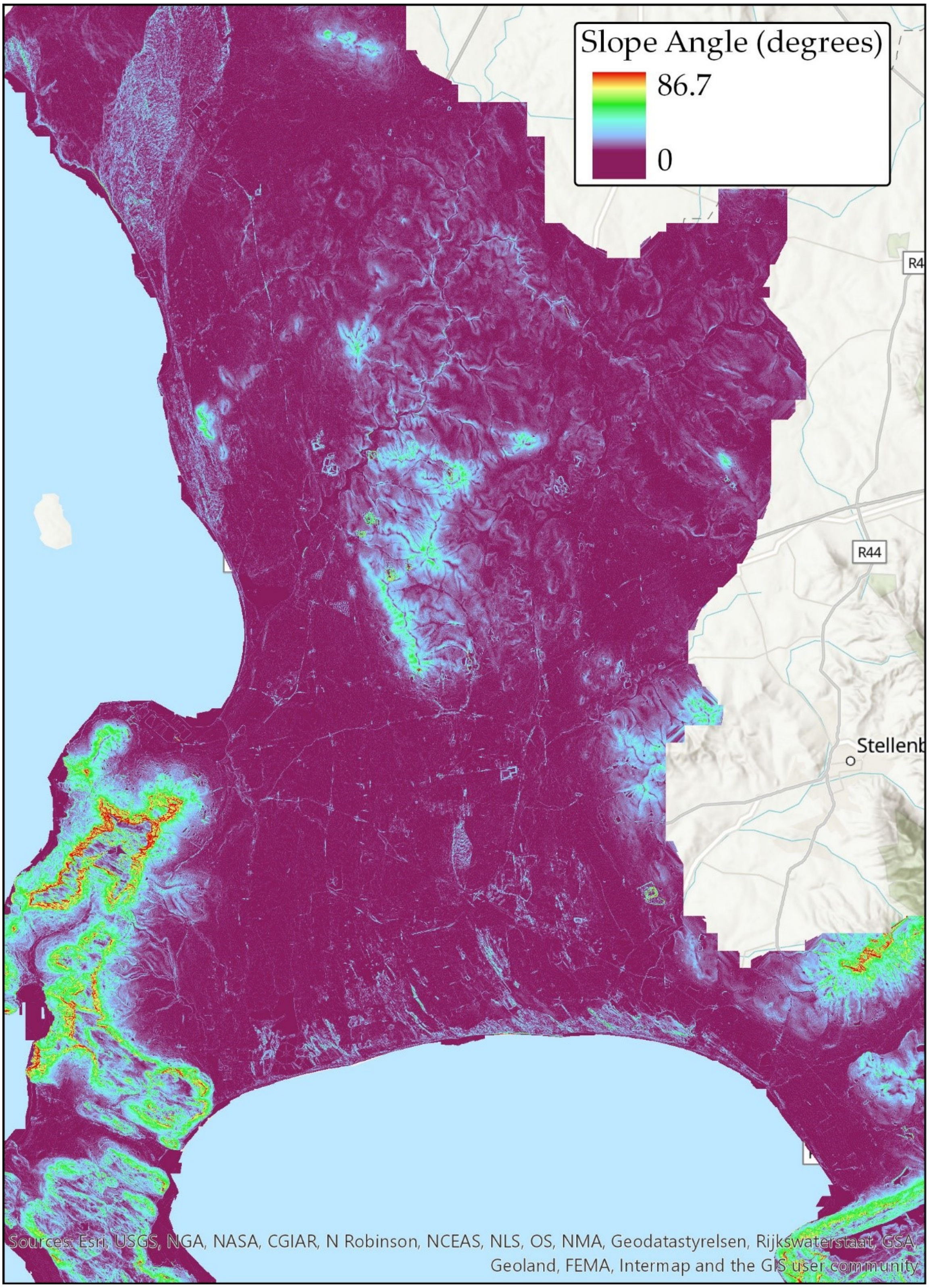


Figure A . 2 - Slope Dataset

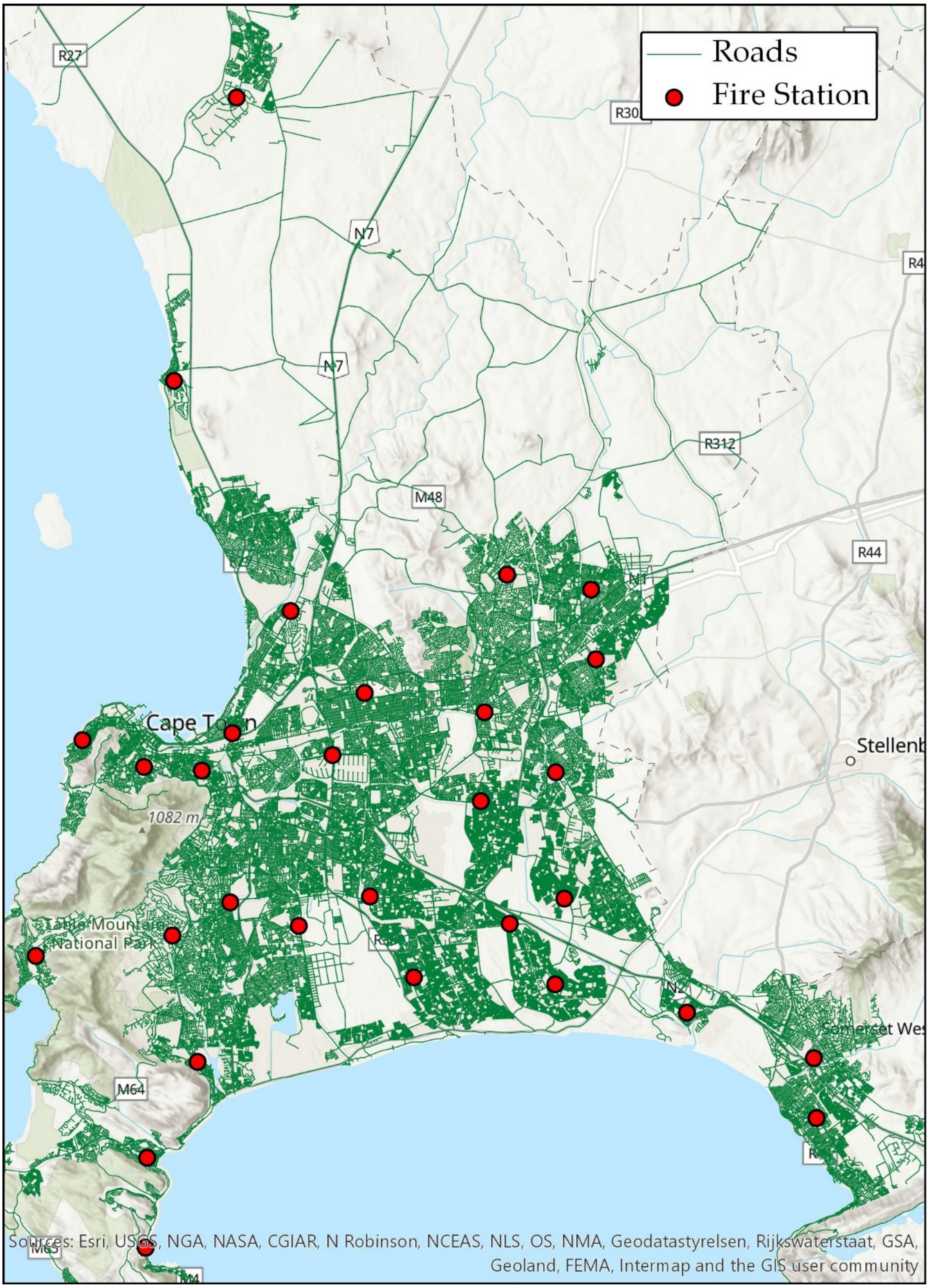


Figure A . 3 - Fire Station and Road Locations Dataset

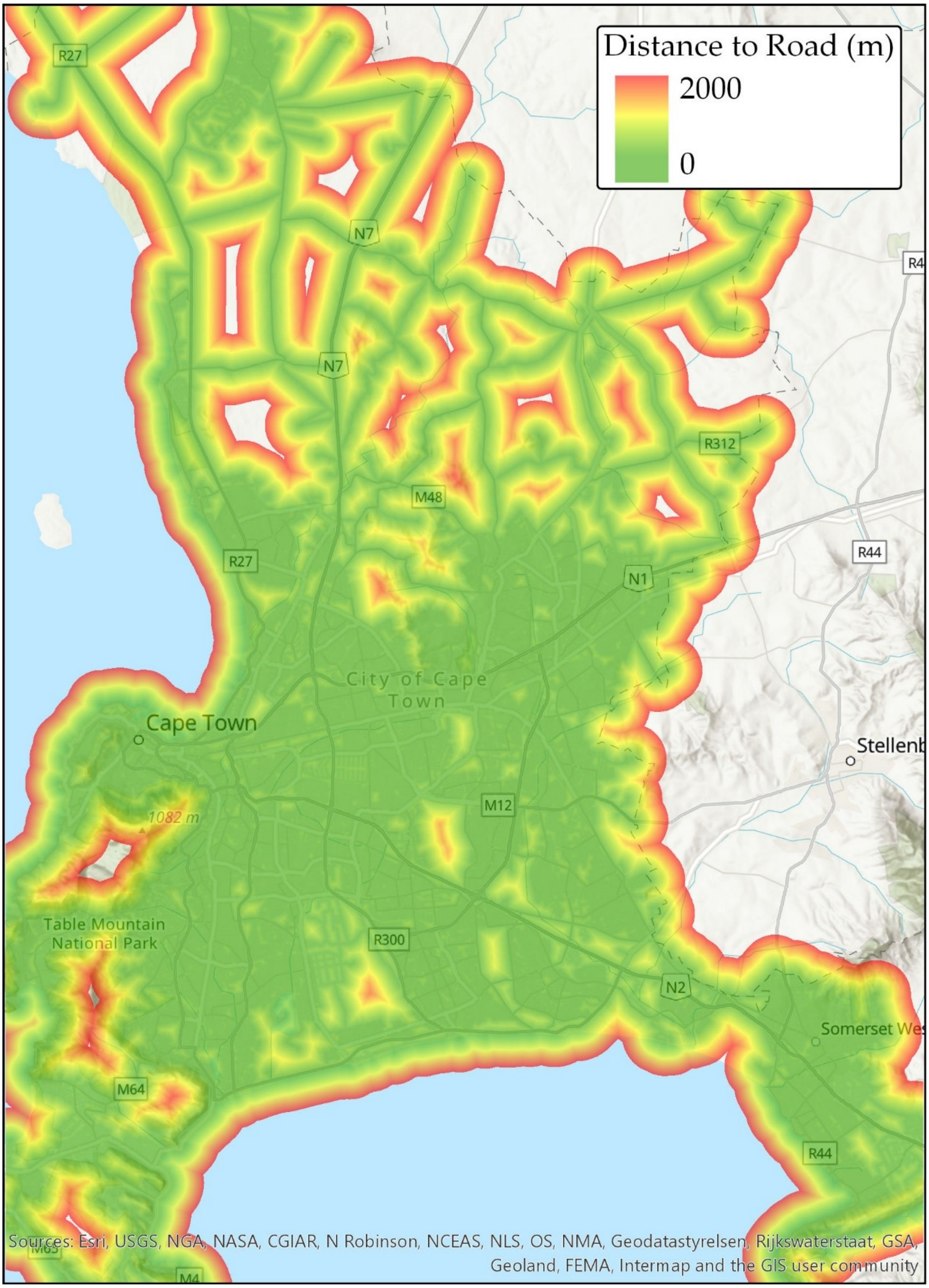


Figure A . 4 - Euclidean Distance from Roads Dataset

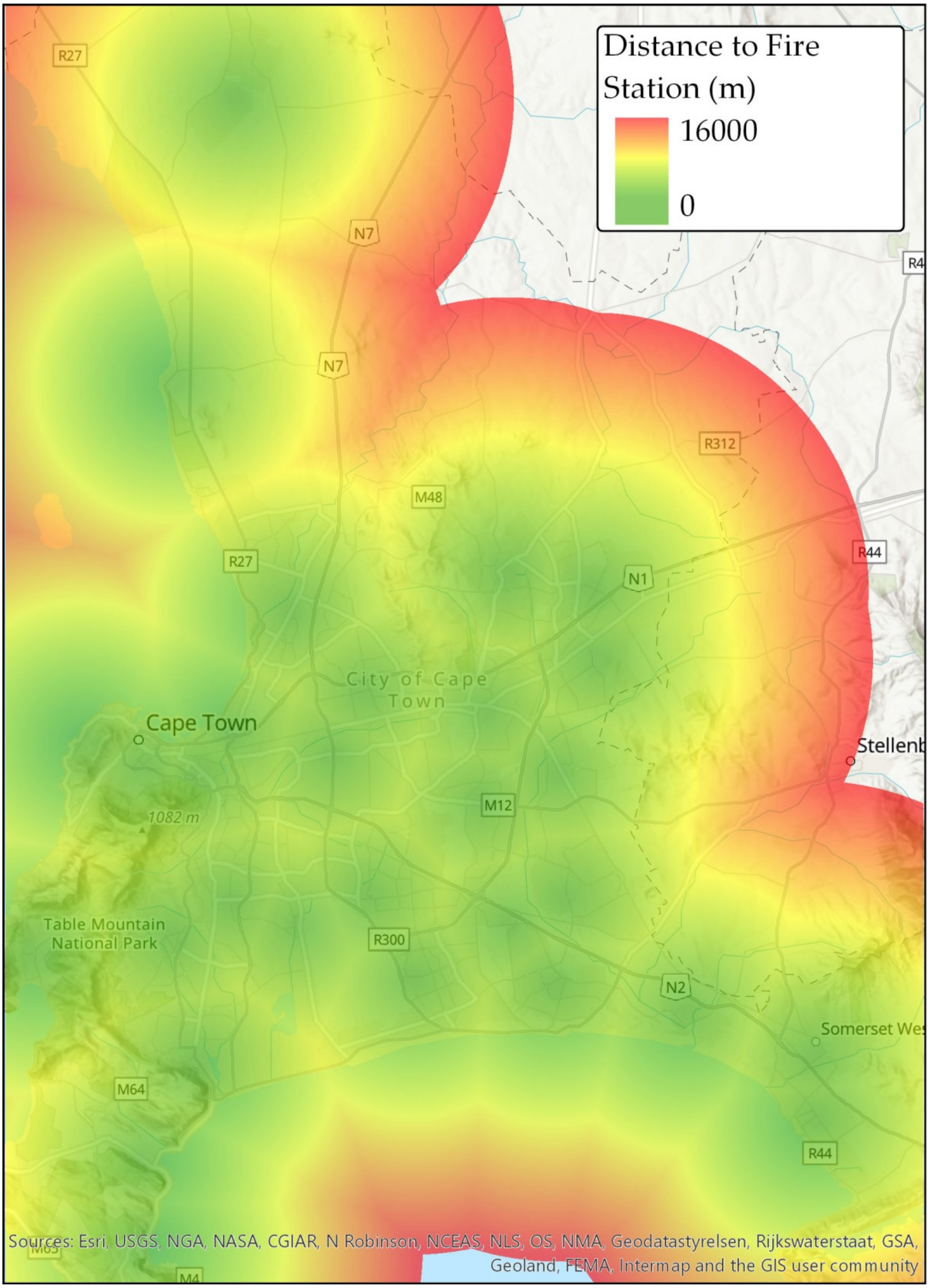


Figure A . 5 - Euclidean Distance from Fire Stations Dataset

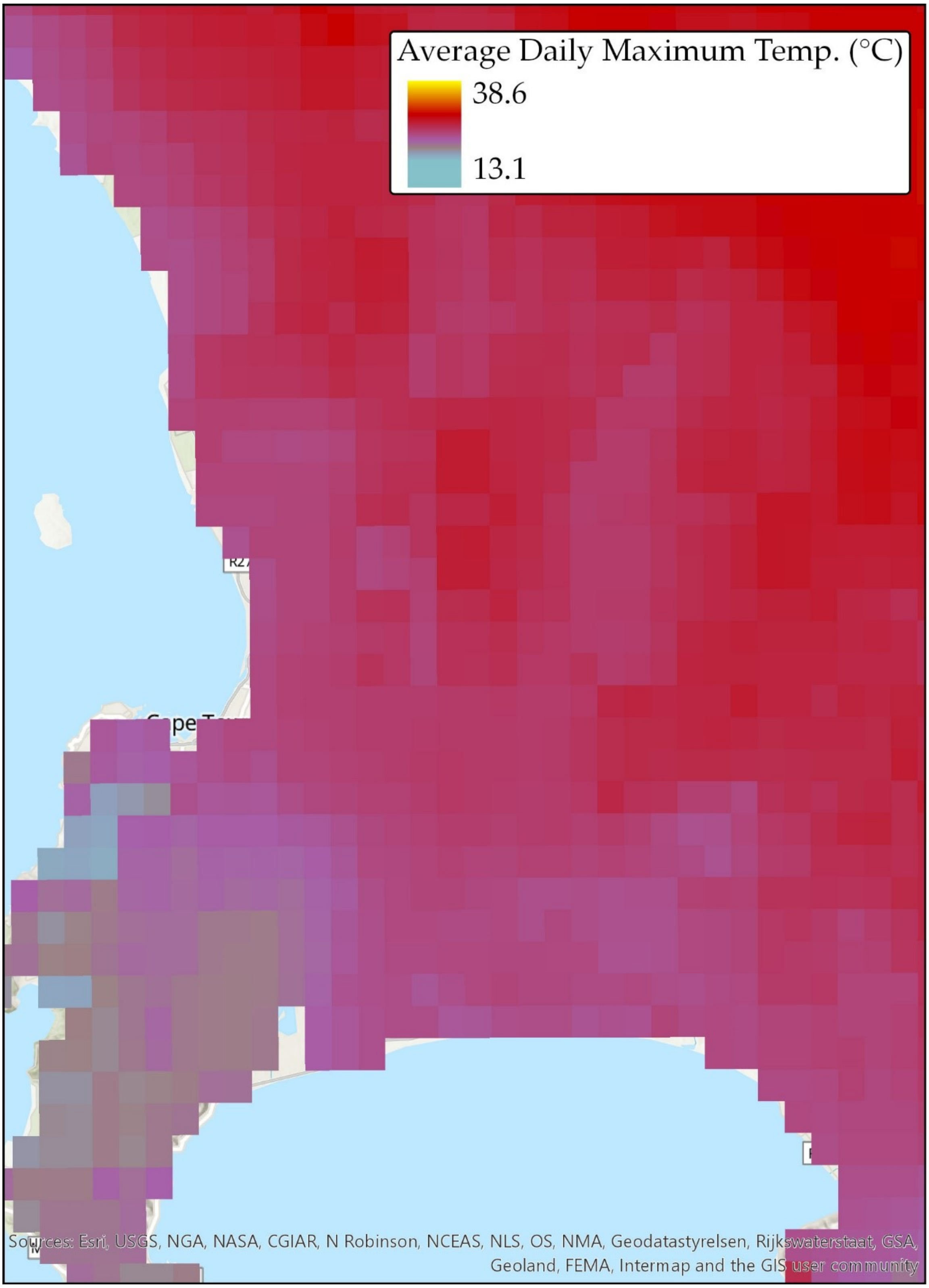


Figure A . 6 - Example Temperature Dataset, Average Daily Maximum Temperature for January

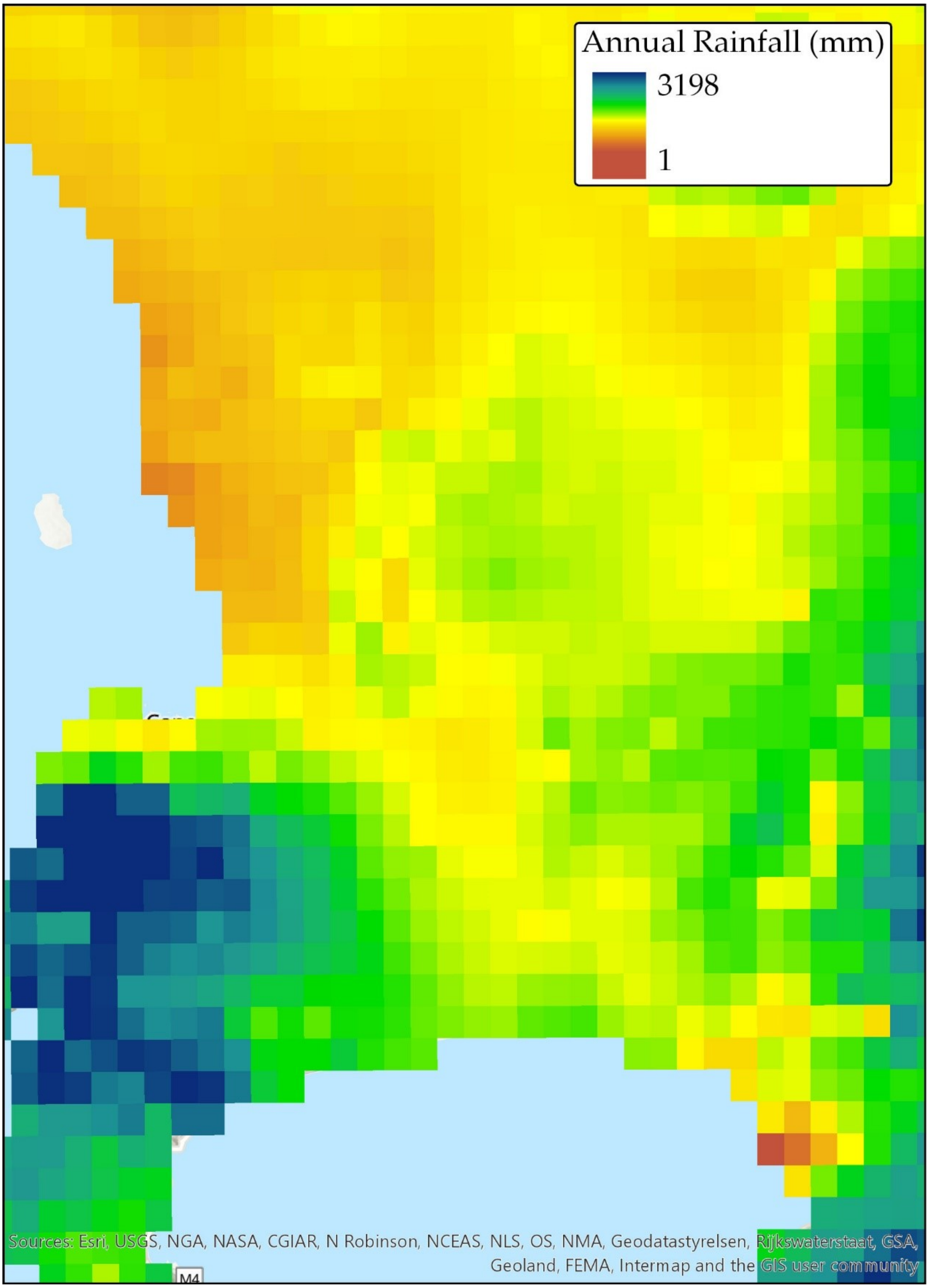


Figure A . 7 - Annual Rainfall Dataset

Appendix B Developed Spatial Factor-Risk Variations

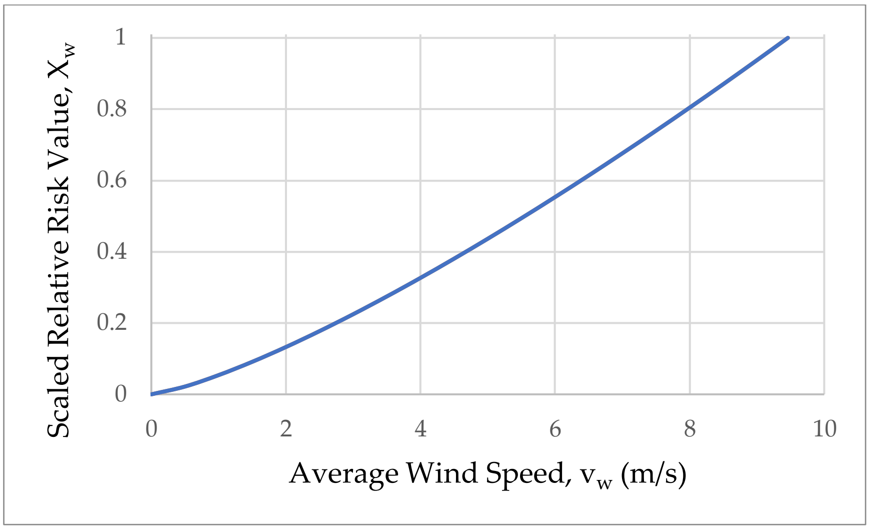


Figure A . 8 - Scaled Relative Risk Variation with Average Wind Speed

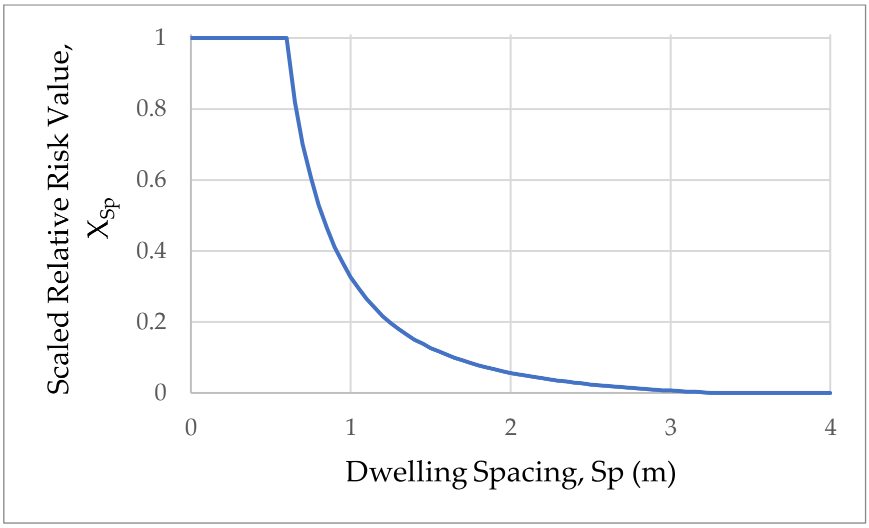


Figure A . 9 - Scaled Relative Risk Variation with Dwelling Spacing

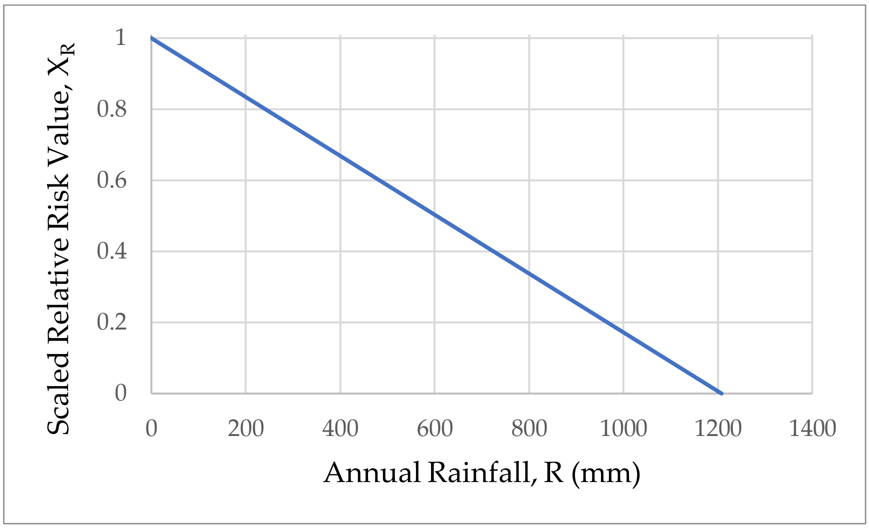


Figure A . 10 - Scaled Relative Risk Variation with Annual Rainfall

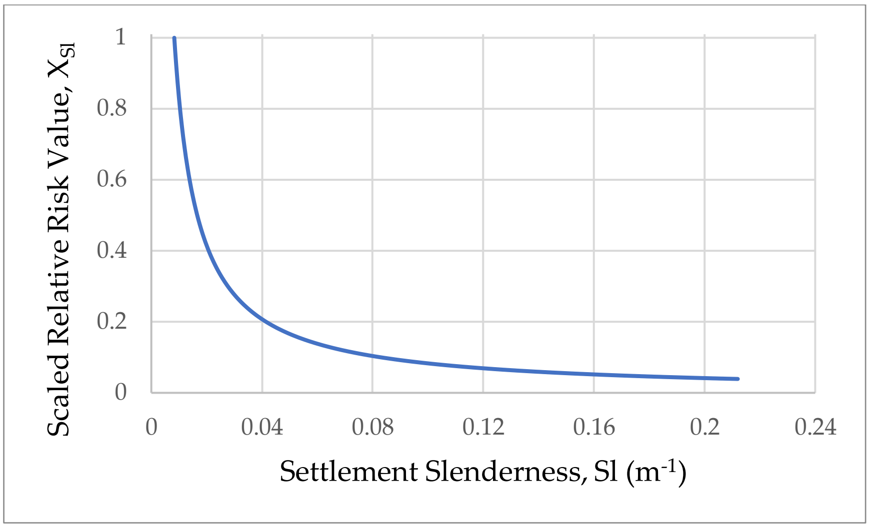


Figure A . 11 - Scaled Relative Risk Variation with Settlement Slenderness

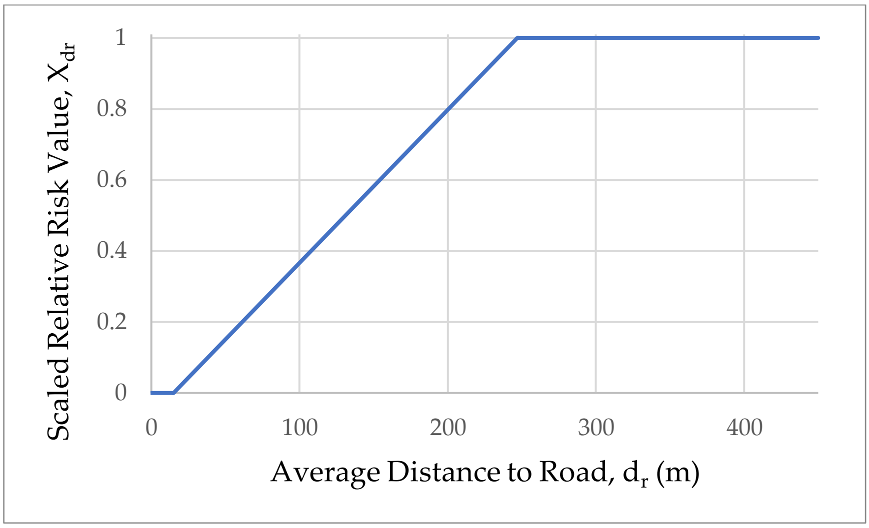


Figure A . 12 - Scaled Relative Risk Variation with Average Distance to Road

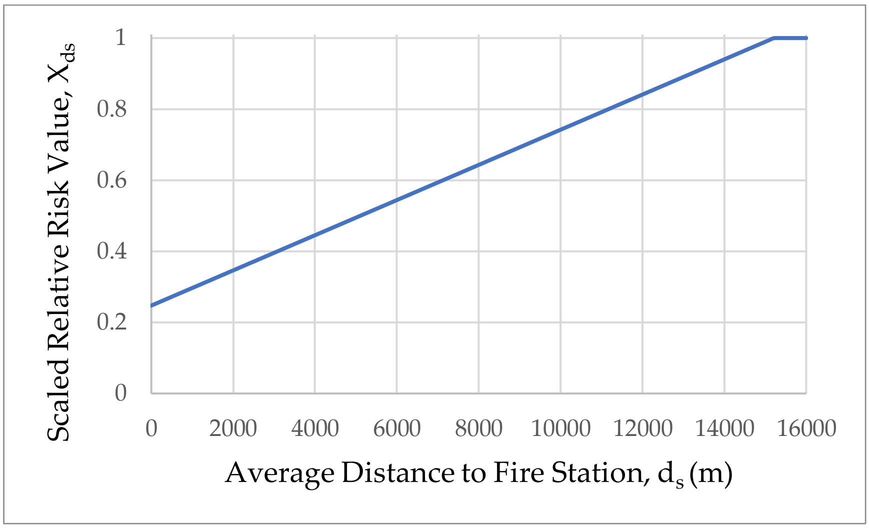


Figure A . 13 - Scaled Relative Risk Variation with Average Distance to Fire Station

Fire risk factors in informal settlements in Cape Town

Page 1: Page 1

Firstly, thank you for taking the time to complete this survey, it is greatly appreciated.

The survey concerns the contribution of the various spatial features of the informal settlement environment to the spread of fire. It is entirely confidential, though it will ask a couple of questions about your general professional experience. It should take no more than 10-15 minutes but please take the time to answer the questions with care. A help sheet is provided to give you the intended definitions of the given spatial factors.

For clarification, take 'informal settlement' to mean a settlement characterised by haphazard dwellings built by residents from any accessible (usually light) material, on land that they may not necessarily have legal rights to. Other names by which you may already know informal settlements are slums, shantytowns, favelas, etc.

The results of this survey will contribute to research regarding the development of a method for mapping relative fire risk across the 250+ informal settlements of Cape Town, South Africa.

Page 2

1. What is your primary field of knowledge and expertise? *Required*

1.a. If you selected Other, please specify:

Key for selection options

1 - What is your primary field of knowledge and expertise?

- Civil/Structural Engineering
- Fire Science and Dynamics
- Sociology
- Geography
- Firefighting
- International Development
- Other

Page 3

2. Have you ever visited an informal settlement? This may have been in any capacity, not strictly professional, and may be any location globally.

- Yes
- No

Page 4

3. Consider a scenario in which ignition has occured in a single informal dwelling, and the dwelling has then become fully involved in the fire. At that moment there are several spatial factors which will influence the extent to which that fire can spread through the surrounding settlement. To the best of your knowledge give these factors a 'weighting' score from 0-10 by the influence they have on fire spread, with 10 being extremely influential and 0 being of no influence. Please refer to the provided help sheet for the definitions of each factor. Please note, this is not asking you to rank the factors against each other from 0-10, so you may choose to assign the same score to multiple factors. ✱ *Required*

Please don't select more than 1 answer(s) per row.

Please select at least 1 answer(s).

	0	1	2	3	4	5	6	7	8	9	10	
Dwelling spacing	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Dwelling spacing
Settlement slenderness	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Settlement slenderness
Average 'critical' patch area	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Average 'critical' patch area
Edge density	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Edge density
Building materials	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Building materials
Fuel load within dwellings	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fuel load within dwellings
Proximity to accessible roads	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Proximity to accessible roads
Proximity to fire hydrants	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Proximity to fire hydrants
Proximity to fire stations	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Proximity to fire stations
Average wind speed	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Average wind speed
Annual rainfall	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Annual rainfall
Topography	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Topography
Daily maximum temperature	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Daily maximum temperature

Page 5: Final page

Many thanks for your time and responses!

If you have any comments or questions, please do not hesitate to contact myself, Sam, at s1332960@ed.ac.uk.

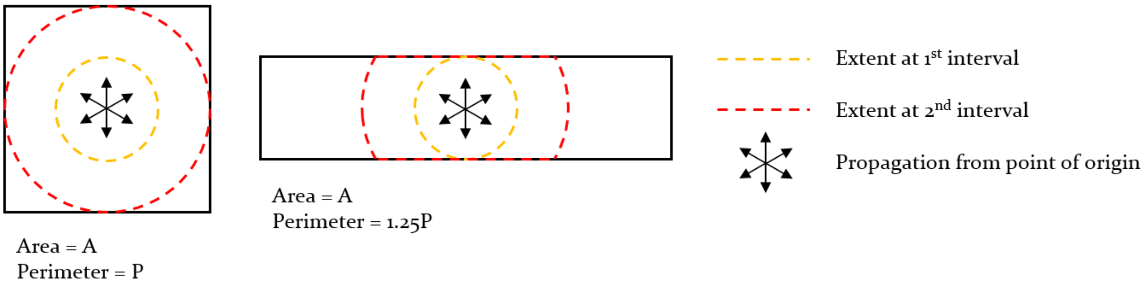
Appendix D Survey Help Sheet

Fire spread in Informal Settlements – Survey Help Sheet

Intended Spatial Factor Definitions

Dwelling spacing – The average minimum distance from one dwelling to the next.

Settlement slenderness – This is the settlement perimeter length divided by its area, and is fundamentally a crude quantifier of the shape of the settlement. A fire in a settlement of greater slenderness (i.e. a larger perimeter to area ratio) will likely cover a smaller area relative to the total area of the settlement prior to reaching, and getting stopped at, the settlement boundary. A basic illustration of this is given below.



Average 'critical' patch area – Previous IRIS-Fire work has established that different building materials have different critical distances for ignition, and by buffering dwelling boundaries to a critical distance we can observe large distinct 'patches' of dwellings within a settlement. It could be assumed that if one dwelling in a ‘patch’ is on fire, surrounding dwellings within the same patch are at much higher risk than dwellings not in the same patch. The larger or more numerous these patches are, the greater the risk to a settlement overall. Below is given a comparison of digitised dwelling rooftops and the interconnected ‘critical’ patches they can form.

Edge density – This is the length of all dwelling perimeter walls per area of the settlement. Fundamentally, this dwelling edge defines a potential pathway for a fire to spread from a dwelling. A greater total length of dwelling edges, the more pathways there are for potential fire spread.

Building materials – The material composition of dwellings, whether that be wood, sheet metal, plastics or otherwise.

Fuel load within dwellings – The contents of dwellings. This is primarily the generic contents of an informal home (furniture, bedding, appliances etc.), but could include extra storage of items such as firewood or other fuels.

Proximity to accessible roads – The average distance of dwellings to a road accessible by fire engines. It could be reasonably assumed that this represents the closest distance that a fire engine can proceed relative to the fire. Many informal settlements in Cape Town may have 'roads' or tracks passing through them, but it cannot be assumed these are accessible as they are often built on or blocked by other obstacles. For some settlements, this means that the central areas of the settlement are far out of reach of the fire service.

Proximity to fire hydrants – The average shortest distance of dwellings to available fire hydrants.

Proximity to fire stations – The travel time from the nearest fire station.

Wind speed – The average wind speed at the settlement. Please consider this in isolation and not in the context of wind direction relative to the topography or settlement. Average wind speeds in Cape Town are typically in the range of 5-10 m/s.

Annual rainfall – The average annual rainfall at the settlement. This fundamentally influences the possible moisture present within the settlement. Settlements that are notably drier over the course of the year may be more at risk. For reference, Cape Town's informal settlements experience annual rainfall levels between approximately 300-1200 mm.

Topography – The average angle of topographical slope on which the settlement is situated. Informal settlements in Cape Town are largely situated on flat planes but the steepest has an average slope in excess of 18°.

Daily maximum temperature – This is the atmospheric temperature at the settlement, and similar to rainfall, is important in influencing the moisture present in the settlement. Please consider this as only an indicator of moisture content. Across Cape Town, informal settlements exhibit a range of more than 5°C in average daily maximum temperature throughout the year. This is significant for the dryness of the settlement but not for fundamental flame spread mechanisms.

Appendix E Full Survey Results

Participant	Field of expertise*	Visited informal settlement?	Factor score (0-10): Dwelling spacing	Settlement slenderness	Critical patch size	Edge density	Building materials	Fuel load	Proximity to accessible roads	Proximity to fire hydrants	Proximity to fire stations	Average wind speed	Annual rainfall	Topography	Daily maximum temperature
01	FSD	Yes	9	5	9	5	10	5	7	6	6	10	4	7	7
02	CSE	Yes	10	6	7	4	9	7	5	6	6	9	2	3	1
03	FSD	No	10	4	7	7	10	10	6	2	2	10	7	8	7
04	CSE	No	8	5	7	5	8	8	7	8	7	8	8	8	8
05	FSD	No	10	2	5	5	10	10	0	0	0	8	2	7	3
06	FSD	No	9	6	6	5	8	8	4	4	6	8	7	7	7
07	CSE	Yes	9	5	7	7	9	8	3	1	1	7	5	5	6
08	ID	Yes	10	5	8	8	10	10	9	9	9	4	4	2	3
09	FSD	Yes	10	6	9	7	9	7	3	5	8	9	3	7	1
10	CSE	Yes	10	2	10	4	7	5	5	5	5	7	2	4	5
Mean			9.5	4.6	7.5	5.7	9.0	7.8	4.9	4.6	5.0	8.0	4.4	5.8	4.8
Standard deviation			0.67	1.43	1.43	1.35	1	1.78	2.43	2.76	2.86	1.67	2.15	2.04	2.48
Median			10.0	5.0	7.0	5.0	9.0	8.0	5.0	5.0	6.0	6.0	4.0	7.0	5.5

*FSD – fire science and dynamics, CSE – civil/structural engineering, ID – international development

Appendix F Pairwise Weight Calculation Method

The basic calculation to populate the first matrix is a comparison of the mean survey score, S, of any two of the factors, i and j, with the difference being converted to a value of comparison between the two factors, β, as follow:

$$\beta_{i,j} = \begin{cases} 1 + (S_i - S_j), & S_i \geq S_j \\ \dfrac{1}{1 + (S_j - S_i)}, & S_i < S_j \end{cases}$$

For n spatial factors, the resultant matrix is of the form:

$$\begin{bmatrix} \beta_{1,1} & \beta_{1,2} & \cdots & \beta_{1,n} \\ \beta_{2,1} & \beta_{2,2} & \cdots & \vdots \\ \vdots & \cdots & \ddots & \vdots \\ \beta_{n,1} & \cdots & \cdots & \beta_{n,n} \end{bmatrix}$$

	Factor, i										
	Dwelling spacing	**Settlement slenderness**	**Critical patch size**	**Edge density**	**Proximity to accessible roads**	**Proximity to fire stations**	**Average wind speed**	**Annual rainfall**	**Topography**	**Daily maximum temperature**	**Sum**
Mean score, S_i	9.44	4.56	7.44	5.44	4.44	4.56	8.44	4.44	6.22	5.00	60

	Dwelling spacing	Settlement slenderness	Average 'critical' patch area	Edge density	Proximity to accessible roads	Proximity to fire stations	Average wind speed	Annual rainfall	Topography	Daily maximum temperature
Dwelling spacing	1	5.889	3.000	5.000	6.000	5.889	2.000	6.000	4.222	5.444
Settlement slenderness	0.170	1	0.257	0.529	1.111	1.000	0.205	1.111	0.375	0.692
Average 'critical' patch area	0.333	3.889	1	3.000	4.000	3.889	0.500	4.000	2.222	3.444
Edge density	0.200	1.889	0.333	1	2.000	1.889	0.250	2.000	0.563	1.444
Proximity to accessible roads	0.167	0.900	0.250	0.500	1	0.900	0.200	1.000	0.360	0.643
Proximity to fire stations	0.170	1.000	0.257	0.529	1.111	1	0.205	1.111	0.375	0.692
Average wind speed	0.500	4.889	2.000	4.000	5.000	4.889	1	5.000	3.222	4.444
Annual rainfall	0.167	0.900	0.250	0.500	1.000	0.900	0.200	1	0.360	0.643
Topography	0.237	2.667	0.450	1.778	2.778	2.667	0.310	2.778	1	2.222
Daily maximum temperature	0.184	1.444	0.290	0.692	1.556	1.444	0.225	1.556	0.450	1
Sum	**3.127**	**24.467**	**8.088**	**17.529**	**25.556**	**24.467**	**5.094**	**25.556**	**13.149**	**20.670**

Each element of the matrix is then divided by the sum of all elements in its column, to 'normalise' each column. The normalised value of comparison, Γ, is therefore:

$$\Gamma_{i,j} = \frac{\beta_{i,j}}{\sum_{i=1}^{n} \beta_{i,j}}$$

Giving a similar matrix of the form,

$$\begin{bmatrix} \Gamma_{1,1} & \Gamma_{1,2} & \cdots & \Gamma_{1,n} \\ \Gamma_{2,1} & \Gamma_{2,2} & \cdots & \vdots \\ \vdots & \cdots & \ddots & \vdots \\ \Gamma_{n,1} & \cdots & \cdots & \Gamma_{n,n} \end{bmatrix}$$

	Dwelling spacing	Settlement slenderness	Average 'critical' patch area	Edge density	Proximity to accessible roads	Proximity to fire stations	Average wind speed	Annual rainfall	Topography	Daily maximum temperature
Dwelling spacing	0.320	0.241	0.371	0.285	0.235	0.241	0.393	0.235	0.321	0.263
Settlement slenderness	0.054	0.041	0.032	0.030	0.043	0.041	0.040	0.043	0.029	0.033
Average 'critical' patch area	0.107	0.159	0.124	0.171	0.157	0.159	0.098	0.157	0.169	0.167
Edge density	0.064	0.077	0.041	0.057	0.078	0.077	0.049	0.078	0.043	0.070
Proximity to accessible roads	0.053	0.037	0.031	0.029	0.039	0.037	0.039	0.039	0.027	0.031
Proximity to fire stations	0.054	0.041	0.032	0.030	0.043	0.041	0.040	0.043	0.029	0.033
Average wind speed	0.160	0.200	0.247	0.228	0.196	0.200	0.196	0.196	0.245	0.215
Annual rainfall	0.053	0.037	0.031	0.029	0.039	0.037	0.039	0.039	0.027	0.031
Topography	0.076	0.109	0.056	0.101	0.109	0.109	0.061	0.109	0.076	0.108
Daily maximum temperature	0.059	0.059	0.036	0.039	0.061	0.059	0.044	0.061	0.034	0.048

The mean value of each row (corresponding to each spatial factor), is then found giving the pairwise weight, W:

$$W_i = \frac{\sum_{j=1}^{n} \Gamma_{i,j}}{10} \ (\times 100\%)$$

	Factor, i										
	Dwelling spacing	**Settlement slenderness**	**Critical patch size**	**Edge density**	**Proximity to accessible roads**	**Proximity to fire stations**	**Average wind speed**	**Annual rainfall**	**Topography**	**Daily maximum temperature**	**Sum**
Pairwise relative weight, W_i (%)	29.04	3.87	14.66	6.35	3.62	3.87	20.83	3.62	9.13	5.01	100

Appendix G Full Risk Model Settlement Rankings

Settlements are listed from highest to lowest by pairwise model rank.

Risk Model	Full Pairwise		Full Standard		Environmental (pairwise)		Interior Infrastructure (pairwise)		Exterior Infrastructure (pairwise)	
Settlement Area Name	**Score out of 100**	**Rank**	**Score out of 100**	**Rank**	**Score out of 38.6**	**Rank**	**Score out of 53.9**	**Rank**	**Score out of 7.5**	**Rank**
Kosovo	67.61	1	59.02	1	19.98	50	44.89	3	2.74	42
BM Section	65.64	2	56.94	3	16.66	216	46.51	1	2.47	56
Dontshiyake	65.38	3	52.88	9	21.42	25	42.04	6	1.92	98
Siyahlala - Du Noon	64.23	4	55.04	7	17.59	181	44.62	4	2.02	89
Sweet Home	64.01	5	55.48	6	19.89	52	41.32	7	2.81	37
DT Section 1	63.41	6	54.26	8	16.73	208	45.03	2	1.65	138
Wetlands	63.05	7	50.58	19	19.79	60	40.51	13	2.75	39
Zululand	61.31	8	48.52	39	19.62	72	38.96	21	2.74	44
KTC	61.22	9	51.11	13	18.65	126	40.95	10	1.62	143
Texas	61.19	10	47.22	55	26.34	2	33.21	178	1.65	139
Hugenote	60.95	11	48.50	40	20.82	30	38.76	22	1.36	223
Doornbach	60.88	12	56.34	4	16.35	235	40.43	14	4.10	11
Klipfontein Glebe COMPACT	60.88	13	55.75	5	17.70	175	40.18	15	3.00	28
BT Section	60.84	14	50.77	15	16.22	243	43.39	5	1.23	276
Wag n' Bietjie 4	60.53	15	50.66	18	21.58	23	36.40	51	2.55	52
Area K	60.36	16	50.76	16	19.13	96	39.35	19	1.88	104
Block 6	60.26	17	50.31	22	19.84	57	38.70	24	1.72	124
Phola Park - Philippi	60.08	18	50.71	17	18.71	119	39.24	20	2.13	76
Lotus	59.77	19	50.38	21	19.23	88	38.07	32	2.46	57
Unknown 1 near Wag n Bietjie	59.65	20	49.36	30	21.89	21	36.00	57	1.76	119
Overcome Heights	59.64	21	46.99	61	19.63	67	38.16	31	1.85	109
Graveyard Pond	59.36	22	49.13	34	20.78	31	37.01	43	1.57	152
Marray	59.35	23	49.70	26	19.08	97	38.39	28	1.88	103
RR Section	59.34	24	51.33	12	16.24	238	41.17	9	1.93	96
Monwood South	59.23	25	49.26	33	18.81	114	38.55	26	1.87	105
Unknown 2 near Wag n Bietjie	59.23	26	49.32	32	21.50	24	35.70	66	2.03	87
Victoria Mxenge 7410 7	59.20	27	49.52	28	16.98	200	40.77	12	1.45	190
Taiwan	59.11	28	50.28	23	16.31	237	41.26	8	1.53	164
Ekuphumleni - Du Noon 3	59.07	29	51.66	10	17.01	194	39.61	18	2.44	58
Zola Square	58.87	30	50.08	24	16.45	228	40.91	11	1.50	177
Amy Biehl	58.76	31	48.62	38	19.19	90	38.06	33	1.51	176
Vukuzenzele	58.71	32	49.56	27	19.07	98	37.72	36	1.93	97
Phola Park – Gugulethu	58.70	33	47.92	44	19.86	54	37.51	37	1.34	234

Europe	58.47	34	51.55	11	18.56	130	37.25	41	2.66	48
Graveyard – Philippi	58.40	35	47.91	45	20.37	38	36.44	50	1.59	148
Unknown near Wag n Bietjie 2	58.36	36	46.64	63	22.72	15	34.17	123	1.47	184
Noqubela TR Section	58.31	37	48.73	36	18.58	129	38.02	34	1.71	127
Link Road School Site	57.91	38	47.71	47	19.44	77	37.04	42	1.42	200
Victoria Mxenge 7410 6	57.85	39	47.70	48	16.67	214	39.66	17	1.52	171
Silvertown	57.85	40	47.51	53	18.45	136	37.95	35	1.45	191
Victoria Mxenge 7410 5	57.75	41	48.08	42	16.23	241	39.85	16	1.67	134
Fisantekraal	57.48	42	50.38	20	17.89	168	36.61	48	2.99	30
YMCA 2	57.38	43	43.82	145	20.50	35	35.76	61	1.12	283
Block 8 - School Site	57.36	44	46.62	64	20.49	37	35.44	71	1.43	195
Greenfields	57.28	45	45.80	81	20.86	29	35.16	84	1.27	267
Monwood Council	57.14	46	46.13	75	19.49	76	36.33	53	1.31	250
Lusaka	56.95	47	47.17	56	17.91	167	37.44	38	1.60	144
Bongani TR Section	56.88	48	48.16	41	16.84	205	38.56	25	1.47	183
Wag n' Bietjie 2	56.80	49	45.49	92	21.98	20	33.32	171	1.51	174
Nomzamo	56.79	50	45.51	89	21.20	27	34.12	126	1.47	185
Letsatsi Mosala Street	56.46	51	45.41	94	20.49	36	34.65	107	1.32	248
Sheffield Road	56.46	52	45.65	86	19.88	53	35.19	81	1.39	211
Site 5 TRA	56.46	53	43.47	156	19.17	94	34.90	93	2.38	61
37B Section	56.39	54	46.51	66	18.92	106	35.62	69	1.85	106
Heinz Park 4	56.39	55	46.48	68	20.21	41	34.63	109	1.55	158
Thabo Mbeki East	56.38	56	48.62	37	16.82	207	37.36	39	2.20	74
Zweledinga	56.35	57	47.56	51	19.06	99	34.80	96	2.48	55
Green Point 1	56.23	58	47.83	46	18.19	151	35.94	58	2.10	80
Small SBDC	56.17	59	46.07	77	19.76	62	35.06	88	1.36	226
Victoria Mxenge 7410 4	56.12	60	47.47	54	15.95	259	38.44	27	1.73	122
Kwaplayithi	56.11	61	45.70	84	19.63	68	34.94	91	1.54	160
Msindweni Makhaza	56.09	62	46.17	73	18.40	142	35.84	60	1.85	107
Monwood	56.05	63	46.43	70	19.26	87	35.40	73	1.39	213
Waterfront	56.05	64	44.90	108	19.62	70	35.11	86	1.31	252
VE Section	56.01	65	47.06	58	15.91	264	38.72	23	1.38	216
Unknown24	56.00	66	44.87	109	19.05	100	35.74	63	1.21	278
Du Noon School Site	55.96	67	48.92	35	16.58	220	37.31	40	2.07	82
Imizamo Yethu 2	55.91	68	43.01	165	20.08	44	34.76	99	1.06	287
Kanana	55.88	69	49.36	31	17.78	172	35.35	76	2.75	40
Heinz Park 2	55.73	70	45.44	93	19.52	74	34.62	110	1.59	147
Siyahlala - Joe Slovo: Milnerton	55.72	71	46.75	62	18.41	141	35.75	62	1.55	156
Victoria Mxenge 7410 1	55.68	72	47.11	57	15.72	274	38.25	29	1.71	126
Iraq	55.65	73	45.31	96	19.18	92	35.08	87	1.39	212
Electrical Servitude - Philippi	55.56	74	44.82	111	19.39	80	34.79	97	1.38	217
KTC Training Camp 1	55.45	75	45.67	85	18.88	108	35.26	79	1.31	256
KTC Training Camp 2	55.43	76	45.83	80	18.38	143	35.74	64	1.31	251
PJS Section	55.42	77	46.50	67	15.82	269	38.16	30	1.45	189
Witsand1	55.42	78	47.57	50	17.88	169	36.14	55	1.40	207
Egoli	55.38	79	43.98	136	16.69	213	36.90	44	1.78	118

K2 Section	55.33	80	46.56	65	16.99	199	36.66	47	1.68	133
Edameni	55.27	81	44.47	120	20.03	47	33.99	132	1.26	269
Phantsikocingo 1	55.27	82	44.60	118	20.25	39	33.70	153	1.32	247
Marcus Garvey	55.27	83	45.00	104	19.77	61	33.74	151	1.76	120
Victoria Mxenge 7410 8	55.24	84	46.34	71	16.56	221	36.88	46	1.80	114
Phantsikocingo 2	55.16	85	44.32	127	19.70	64	34.15	124	1.31	253
Tsunami : Samora Machel	55.12	86	44.50	119	19.27	86	34.44	115	1.41	205
Phillipi Site	55.10	87	44.66	116	19.82	58	33.85	141	1.42	199
Sheffield Ingulube	55.07	88	43.86	143	19.85	56	33.93	136	1.29	264
Kansite	55.01	89	44.16	130	20.13	42	33.46	162	1.42	202
Tsepe Tsepe	55.01	90	45.54	88	17.08	192	36.34	52	1.59	146
Samora Machel	54.99	91	44.13	133	18.82	112	34.86	94	1.31	249
Unknown25	54.98	92	44.13	132	19.18	93	34.52	114	1.28	265
Lower Chris Hani	54.94	93	47.65	49	20.03	46	32.71	183	2.21	71
Heinz Park 3	54.90	94	44.46	122	19.50	75	33.85	140	1.55	159
Heinz Park 5	54.76	95	44.14	131	20.01	48	33.19	180	1.56	154
YAB Section 1	54.75	96	45.78	82	17.16	189	36.25	54	1.34	238
Galaweni Road	54.69	97	43.89	141	19.19	91	34.11	128	1.39	210
Zwelitsha Drive	54.68	98	44.71	115	18.38	144	34.90	92	1.40	206
Ezihagwini	54.63	99	43.90	140	19.04	101	34.22	122	1.36	224
Sakhile	54.60	100	45.14	102	18.36	147	34.74	101	1.50	178
Wallacedene TRA	54.60	101	47.04	59	17.02	193	35.50	70	2.08	81
Ekuphumleni - Joe Slovo: Milnerton	54.59	102	45.77	83	17.83	170	35.39	74	1.37	220
Jameson Mngomezulu Road	54.48	103	43.75	148	19.30	85	33.72	152	1.46	187
Joe Slovo	54.46	104	46.20	72	16.84	206	35.33	78	2.29	64
Sonwabile Road 1	54.43	105	44.42	123	18.98	104	33.92	137	1.54	162
Riemvasmaak	54.43	106	43.93	139	16.53	225	35.72	65	2.18	75
Mashlungi	54.42	107	44.78	112	19.20	89	33.51	156	1.72	123
Browns Farm 5	54.33	108	43.54	150	19.85	55	33.26	174	1.23	277
Lindelani Park	54.30	109	44.87	110	17.81	171	35.17	82	1.32	243
WB Section	54.27	110	45.50	91	16.04	253	36.90	45	1.33	239
Mchiniwham	54.27	111	45.05	103	18.44	138	34.39	118	1.44	194
Sagwityi Street	54.21	112	43.51	154	19.17	95	33.58	155	1.46	186
Du Noon TRA	54.21	113	48.03	43	16.56	222	33.98	133	3.66	18
Thembisa	54.16	114	43.16	160	19.33	84	33.49	161	1.34	237
Block 8 - Open Space	54.14	115	43.11	161	19.41	78	33.49	159	1.24	273
Oliver Tambo Avenue	54.12	116	44.04	135	18.86	109	33.91	138	1.35	230
1	54.12	117	46.43	69	18.18	153	34.61	111	1.33	241
Monwabisi Park B	54.10	118	57.67	2	23.15	11	25.96	210	4.99	4
B Longo Road 1	54.09	119	43.93	138	18.38	145	34.39	117	1.33	242
Graveyard - Hout Bay	54.07	120	41.05	206	18.75	117	33.97	134	1.35	231
Stulo Road 1	54.05	121	43.95	137	18.65	124	33.91	139	1.49	179
Lansdowne Road 2	54.03	122	44.46	121	17.99	164	34.34	120	1.70	129
P Section	54.03	123	44.73	113	18.18	152	34.64	108	1.20	279
Island - Bongani	54.02	124	45.19	100	16.99	197	35.67	68	1.35	227
Lansdowne Road 1	53.93	125	44.39	124	18.21	150	34.13	125	1.60	145

Victoria Mxenge 7410 3	53.87	126	45.90	79	16.12	249	35.22	80	2.54	53
Stulo Road 6	53.85	127	43.79	146	18.94	105	33.39	165	1.52	169
Unknownnear Klipfontein	53.83	128	45.31	97	16.15	246	35.89	59	1.79	116
Victoria Mxenge 7410 2	53.82	129	44.94	107	16.10	250	36.03	56	1.69	132
Stulo Road 4	53.72	130	43.53	152	18.55	131	33.68	154	1.48	181
Du Noon Business Site	53.67	131	46.12	76	16.40	231	35.43	72	1.85	108
Mpetha Square	53.52	132	43.02	164	18.67	122	33.29	173	1.56	153
B Longo Road 2	53.48	133	42.96	167	18.70	120	33.46	163	1.32	245
AT Section 4	53.41	134	43.78	147	15.61	278	36.48	49	1.32	246
Ithembeni 2	53.34	135	45.59	87	16.71	210	34.82	95	1.81	113
CCT Section	53.34	136	45.23	99	15.94	261	35.34	77	2.06	84
Thabo Mbeki West	53.29	137	47.00	60	17.67	178	33.35	167	2.27	67
Sunbird Park	53.28	138	46.16	74	15.80	270	34.56	112	2.92	33
Great Dutch Street 1	53.26	139	43.35	158	17.77	173	34.11	127	1.38	215
Butter 50	53.23	140	42.44	179	18.51	135	33.34	169	1.38	214
Ekuphumleni - Du Noon 2	53.18	141	45.26	98	16.12	248	35.16	83	1.90	100
Joe Slovo North	53.16	142	43.51	153	18.09	162	33.49	160	1.57	150
Mbambo Street 1	53.15	143	42.75	172	18.53	133	33.36	166	1.26	270
Bekela 1	53.04	144	43.87	142	18.37	146	33.23	177	1.44	193
Mocke Road	53.03	145	41.86	192	17.24	186	33.50	157	2.29	65
Ekuphumleni - Du Noon 1	53.01	146	45.36	95	16.24	239	34.74	100	2.03	88
Sagoloda Street 2	52.95	147	41.68	196	19.33	83	32.21	189	1.41	204
VT Section	52.95	148	44.28	128	15.99	257	35.70	67	1.26	268
Du Noon Holding Site 3	52.88	149	44.98	106	16.39	233	34.66	106	1.83	111
Khwezi Park	52.83	150	44.13	134	16.62	219	34.69	105	1.52	170
Witsand2	52.77	151	44.71	114	18.01	163	33.45	164	1.31	255
Great Dutch Street 3	52.73	152	42.42	180	18.41	140	32.94	182	1.37	218
Unknown near Joe Slovo	52.69	153	43.18	159	17.44	183	33.32	170	1.93	95
Sollys Town	52.66	154	45.91	78	20.78	32	29.61	195	2.28	66
Tsunami TRA	52.59	155	45.17	101	15.75	273	35.12	85	1.72	125
Unknown31	52.47	156	43.40	157	16.32	236	34.71	103	1.43	196
Block Macassar	52.46	157	41.42	200	18.92	107	32.20	190	1.35	232
Sixth Avenue - Kensington	52.46	158	42.57	173	17.00	196	33.82	146	1.64	140
Terminus Street	52.35	159	41.31	201	18.74	118	32.36	187	1.25	271
Nyakathisa	52.33	160	43.53	151	15.54	281	35.36	75	1.43	197
Kalkfontein	52.28	161	44.64	117	15.95	258	34.37	119	1.96	93
NT Section	52.28	162	43.49	155	15.95	260	35.02	89	1.32	244
Sewende Laan - Valhalla Park	52.25	163	42.80	169	17.23	187	33.20	179	1.82	112
Gxagxa	52.18	164	42.57	174	17.28	185	33.23	176	1.67	135
Z Memani Road	52.17	165	41.92	191	18.84	110	32.03	191	1.30	260
Pook Se Bos	52.17	166	41.75	195	16.46	227	33.50	158	2.21	72
YAB Section 3	52.14	167	42.75	171	17.11	191	33.74	150	1.30	261
Unknown Jakes Gerwels Dr	52.05	168	49.43	29	19.93	51	28.34	203	3.77	15
Unknown33	51.93	169	41.81	193	16.72	209	33.85	143	1.36	225
Mlambo Street	51.91	170	42.96	166	16.02	255	34.72	102	1.18	281
UTR Section	51.84	171	42.48	176	16.93	203	33.79	147	1.12	285

AT Section 1	51.72	172	43.03	163	15.89	266	34.54	113	1.29	262
LR Section	51.71	173	42.21	185	16.47	226	33.84	144	1.40	208
Peter Tosh	51.71	174	42.75	170	15.63	277	34.77	98	1.31	254
Great Dutch Street 2	51.69	175	41.13	204	17.76	174	32.54	186	1.40	209
Makhanya Crescent	51.60	176	42.04	189	17.13	190	33.31	172	1.16	282
LB Section	51.60	177	42.36	183	16.22	242	33.85	142	1.52	167
Unknown9	51.56	178	43.62	149	15.24	287	35.01	90	1.31	258
New Rest 2	51.55	179	41.95	190	16.64	217	33.13	181	1.79	117
Vygieskraal	51.50	180	41.10	205	15.68	275	33.76	149	2.06	85
QA Section	51.40	181	42.16	186	16.05	251	34.06	130	1.29	263
Ciko Avenue	51.31	182	42.08	188	15.84	267	34.40	116	1.07	286
Siyahlala - Langa	51.31	183	40.85	209	15.84	268	33.94	135	1.53	166
Siyakha Street	51.30	184	42.10	187	16.17	244	34.02	131	1.12	284
AT Section 2	51.30	185	42.37	182	16.24	240	33.82	145	1.24	274
Boys Town	51.29	186	43.05	162	18.10	161	31.20	192	1.99	90
AT Section 3	51.21	187	42.32	184	15.27	286	34.71	104	1.23	275
Esigingqini	51.10	188	47.54	52	19.40	79	28.62	201	3.08	27
Monwabisi Park A	51.06	189	50.98	14	22.80	14	25.07	211	3.19	24
V Section	51.06	190	41.78	194	15.79	272	34.23	121	1.04	289
DT Section 2	50.99	191	41.61	198	15.90	265	34.06	129	1.02	290
Unknown3	50.97	192	42.44	178	16.00	256	33.35	168	1.62	142
DT Section3	50.93	193	41.56	199	16.17	245	33.77	148	1.00	291
Unknown27	50.56	194	39.28	217	16.39	232	32.63	185	1.53	165
Thabo Mbeki - Zone 1: Langa	50.50	195	40.23	216	16.36	234	32.70	184	1.45	188
Gqobasi	50.39	196	42.52	175	18.83	111	29.77	194	1.79	115
Umbashe Street 1	50.28	197	40.88	208	15.67	276	33.26	175	1.35	233
Jim Se Bos	50.28	198	42.46	177	18.65	125	29.04	198	2.58	50
Beverley Hills	50.24	199	41.64	197	22.80	13	26.25	207	1.18	280
Unknown19	50.19	200	42.38	181	20.09	43	28.68	200	1.43	198
Hadji Ebrahim Crescent	49.84	201	39.13	219	15.56	279	32.29	188	1.99	91
3	49.81	202	42.95	168	18.16	156	30.31	193	1.34	236
Unknown Savage and Lovemore	49.66	203	44.16	129	23.37	10	24.19	212	2.11	79
Silvertown TRA	49.19	204	43.86	144	17.35	184	29.10	197	2.73	45
Unknown Military Rd	48.30	205	37.57	225	18.64	127	27.91	204	1.76	121
Unknown18	48.19	206	40.40	213	20.22	40	26.63	205	1.34	235
Unknown8	46.27	207	40.48	212	15.45	282	29.49	196	1.33	240
Witsand4	46.24	208	44.39	125	18.53	134	26.05	209	1.66	136
Estendini	45.95	209	45.50	90	19.74	63	23.21	213	2.99	29
Unknown10	45.55	210	40.73	211	15.34	284	28.95	199	1.25	272
Unknown7	45.40	211	38.37	221	15.42	283	28.43	202	1.55	157
Monwabisi Park C	45.35	212	49.90	25	22.87	12	17.70	235	4.78	5
Klein Zoute Rivier	45.09	213	44.36	126	18.53	132	21.01	222	5.55	2
Phumlani	44.64	214	36.56	232	16.99	198	26.10	208	1.56	155
Hangberg	44.24	215	40.26	215	29.71	1	12.09	251	2.43	59
Special Quarters	44.23	216	36.97	228	16.40	230	26.31	206	1.52	168
Unknown near Zweledinga	44.22	217	40.30	214	21.65	22	20.69	225	1.89	102

Pholile	44.01	218	40.80	210	20.65	34	21.30	221	2.07	83
Barcelona	43.20	219	44.98	105	18.11	159	21.46	220	3.63	19
Hillview 2	42.74	220	37.85	224	19.99	49	20.08	228	2.66	47
Gwayi Road 1	42.67	221	37.50	226	19.00	102	22.13	219	1.54	163
Dallas	42.60	222	35.94	237	24.69	6	15.97	237	1.94	94
Savage And Lovemore	42.54	223	38.75	220	24.13	7	15.85	239	2.56	51
Unknown28	41.97	224	36.75	229	19.62	71	20.88	223	1.47	182
2	41.94	225	39.27	218	17.92	166	22.53	215	1.48	180
Sihlanu Avenue	41.92	226	36.44	233	18.15	157	22.41	216	1.35	228
Unknown26	41.61	227	35.42	239	19.34	82	20.70	224	1.57	151
Zwelitsha 1	41.13	228	41.27	202	19.38	81	19.35	230	2.40	60
Monwabisi Park M	41.11	229	41.20	203	23.79	8	15.01	241	2.30	62
Section 36	40.87	230	35.83	238	18.82	113	20.53	227	1.52	172
Canal Walk	40.82	231	32.95	253	16.14	247	23.13	214	1.54	161
Chris Hani	39.85	232	37.87	223	19.57	73	18.16	234	2.11	77
Driftsands	39.67	233	36.67	230	15.55	280	22.15	218	1.97	92
Unknown6	39.37	234	36.08	236	17.69	177	19.97	229	1.70	128
Better Life - Mfuleni	38.68	235	34.14	246	15.09	288	22.32	217	1.27	266
Mkonto Square	38.39	236	34.82	243	18.78	115	18.31	233	1.30	259
Thambo Square	38.33	237	33.78	248	18.26	149	18.66	232	1.42	203
Unknown30	38.24	238	37.89	222	16.04	252	20.61	226	1.58	149
Kampies	37.18	239	33.36	252	17.01	195	17.23	236	2.94	32
Garden Cities - Mfuleni	36.97	240	34.88	241	16.94	202	18.99	231	1.04	288
Newlands	36.22	241	36.42	234	19.82	59	14.11	244	2.29	63
Freedom Park - Ottery	35.64	242	34.82	242	15.09	289	15.86	238	4.70	7
Jabula	35.43	243	32.59	256	18.42	139	14.10	245	2.91	34
Smallville	34.63	244	36.29	235	18.77	116	10.52	255	5.33	3
Burundi - Mfuleni	33.86	245	37.20	227	15.34	285	15.03	240	3.49	20
Makhaza Road Reserve	33.69	246	31.41	267	17.97	165	14.22	243	1.51	175
Macassar Village	33.49	247	32.90	254	18.17	154	13.05	247	2.26	69
Shukushuma - Mfuleni	33.26	248	33.62	249	17.69	176	13.87	246	1.70	130
Klipheuwel	33.12	249	41.05	207	18.17	155	8.87	259	6.08	1
Febhana	32.71	250	31.65	264	18.67	121	12.62	249	1.42	201
Village Heights	32.51	251	32.14	260	20.07	45	9.70	257	2.74	43
Agste Laan - Valhalla Park	32.51	252	33.95	247	16.67	215	13.01	248	2.83	36
The Ark	32.50	253	35.36	240	20.74	33	8.58	261	3.18	25
Philedelphia	32.41	254	36.61	231	19.67	66	9.26	258	3.48	21
Unknown2	32.30	255	31.84	263	15.93	263	14.75	242	1.63	141
7D Laan - Strandfontein	32.29	256	33.49	250	24.83	5	4.50	273	2.96	31
Unknown near Macassar	32.25	257	30.76	272	18.45	137	12.45	250	1.35	229
Rasta Camp - Sir Lowrys Pass	32.16	258	32.36	257	22.70	16	6.94	265	2.52	54
Masincedane Camp	31.63	259	34.30	244	23.63	9	4.31	274	3.68	17
Red Hill	31.43	260	33.40	251	25.54	3	2.75	282	3.14	26
Dark City	31.18	261	30.77	271	22.15	19	7.13	264	1.90	99
Pine Town	31.01	262	34.22	245	24.86	4	1.68	289	4.47	9
Springfield Road	30.55	263	28.82	279	16.04	254	11.73	252	2.79	38

Witsand3	30.49	264	32.10	261	18.15	158	11.04	253	1.31	257
Morkels Cottages	30.32	265	30.58	273	21.33	26	7.34	263	1.66	137
Sweet Lips	30.22	266	31.43	266	17.18	188	10.99	254	2.05	86
Unknown4	29.24	267	30.97	269	16.55	224	9.98	256	2.72	46
Unknown21	29.13	268	29.64	276	18.98	103	8.63	260	1.51	173
Witsand	29.10	269	32.06	262	19.69	65	8.04	262	1.37	219
Rasta Camp - Ocean View	29.03	270	31.46	265	22.69	17	1.79	288	4.55	8
Uitkyk	27.91	271	30.14	274	22.52	18	1.91	287	3.48	22
Phillipi TRA	27.81	272	30.95	270	18.61	128	6.46	266	2.74	41
Unknown1	26.21	273	29.62	277	17.64	179	6.35	267	2.22	70
Unknown near Witsand	26.09	274	32.85	255	20.88	28	3.01	279	2.20	73
Los Angeles	25.76	275	32.21	259	16.88	204	4.71	272	4.16	10
Unknown 2 near Witsand	24.94	276	28.24	281	18.66	123	4.84	271	1.44	192
Freedom Park Airport	24.45	277	31.30	268	16.64	218	3.75	276	4.06	12
City Mission - Crossroads	23.96	278	29.41	278	18.28	148	1.95	286	3.73	16
Unknown23	23.83	279	23.77	288	15.94	262	5.78	268	2.11	78
Green Park	23.66	280	32.30	258	15.80	271	3.11	278	4.75	6
Unknown5	23.26	281	25.55	286	17.60	180	3.97	275	1.69	131
Dassenberg Drive	23.08	282	27.87	282	19.62	69	1.19	291	2.27	68
Malawi	22.94	283	30.03	275	16.44	229	2.73	283	3.78	14
Boys Town 1	22.82	284	27.75	283	17.51	182	2.48	285	2.83	35
Cata	22.77	285	22.02	291	16.55	223	4.85	270	1.36	222
De Waal Road	22.76	286	23.19	289	16.70	212	3.45	277	2.61	49
4 In 1	22.60	287	26.06	285	15.04	290	5.67	269	1.90	101
Klipfontein Glebe	22.54	288	28.54	280	16.71	211	2.52	284	3.31	23
Witsand5	22.27	289	26.51	284	18.11	160	2.80	281	1.37	221
Bonny Town Bush	21.98	290	24.76	287	14.96	291	2.99	280	4.03	13
Maitland Cemetery Gate 1	20.00	291	22.53	290	16.96	201	1.21	290	1.83	110